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Capabilities and Prospects for Improvement in Aircraft Icing Simulation Methods: Contributions to the 11C Working Group

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Final Report

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16. Abstract

This collection of papers is a product of Task 11C of the Federal Aviation Administration (FAA) Aircraft In-flight Icing Plan. The papers are of two types. Industry users of icing simulation tools (facilities and computer codes) contributed articles describing how icing simulation methods are used in the design process and the certification process by their industry segment. These contributions include discussion of limitations of current tools and of gaps arising from differences between simulation needs and current capabilities. A table summarizing gaps noted by different industry users and recommendations for improvement is included in appendix C to this report. Examination of the table reveals several major concerns. One such concern is the development of criteria and validation data, as necessary, for acceptance of simulation tools in certification. A large number of recommendations are listed for icing analysis computer codes. Increased use of these codes is attractive to industry in part because of their potential for improvements in cost/flow time in the design and certification processes. Issues of validation data and acceptance criteria are recognized as especially relevant to icing analysis computer codes.

Providers and developers of icing simulation tools contributed articles summarizing the capabilities currently available in their respective areas. They address issues such as range of capabilities, accuracy, repeatability, and ease of use. They also list limitations of the simulation methods in terms of how well they function with respect to their stated purpose and how well they simulate natural icing encounters.

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EXECUTIVE SUMMARY

This collection of papers is a product of Task 11C of the Federal Aviation Administration (FAA) Aircraft In-Flight Icing Plan, which called for the FAA to "support research on the development and improvement of ice simulation methods such as ice accretion codes, icing tunnels, and icing tankers." The papers are of two types. Industry users of icing simulation tools (facilities and computer codes) contributed articles describing how icing simulation methods are used in the design process and the certification process by their industry segment. These contributions include discussion of limitations of current tools and of gaps arising from differences between simulation needs and current capabilities. This information is useful to government research organizations in the development of research investment strategies for the improvement of icing simulation facilities and methods. A table summarizing gaps noted by different industry users, and recommendations for improvement is included in appendix C to this report. Examination of the table reveals several major concerns. One such concern is the development of criteria and validation data, as necessary, for acceptance of simulation tools in certification. A large number of recommendations are listed for icing analysis computer codes. Increased use of these codes is attractive to industry in part because of their potential for improvements in cost/flow time in the design and certification processes. Issues of validation data and acceptance criteria are recognized as especially relevant to icing analysis computer codes.

Providers and developers of icing simulation tools contributed articles summarizing the capabilities currently available in their respective areas. They address issues such as range of capabilities, accuracy, repeatability, and ease of use. They also list limitations of the simulation methods in terms of how well they function with respect to their stated purpose and how well they simulate natural icing encounters. Limitations are not concerned strictly with how well natural conditions are simulated, but also with how well facilities perform with respect to desired functionality, over what range of desired conditions, with what degree of accuracy, and with what amount of repeatability.

INTRODUCTION

Task 11C of the Federal Aviation Administration (FAA) Aircraft In-Flight Icing Plan (April 1997, see appendix A) called for the FAA to "support research on the development and improvement of ice simulation methods such as ice accretion codes, icing tunnels, and icing tankers." In pursuit of this goal, a working group was formed under the joint leadership of the FAA and National Aeronautics and Space Administration (NASA) in November 1997 to consider effective investment in improvement of simulation capabilities.

The working group included both users of icing simulation methods and developers and providers of icing simulation tools. The users included representatives of the general aviation, business jet, and commuter industries, the large transport aircraft industry, the helicopter industry, the engine industry, and the ice protection industry. The developers and providers included representatives of icing wind tunnels, icing tankers, environmental chambers, and computer codes. (See appendix B for a list of all working group members and attendees.)

At its second meeting, the working group established an outline for a consensus working group report. The report was to incorporate contributions from both users and developers, and some excellent contributions were received. This material has been and continues to be used by government research organizations in the development of research investment strategies for the improvement of icing simulation methods, both experimental and computational. Although the 11C Working Group did not develop a consensus report, the articles submitted are of general interest, and are published here to document the work and findings of the group.

Users contributed articles describing how icing simulation methods are used in the design process or in the certification process by their industry segment. Most contributions conform to some degree to general guidelines that were established for the user contributions, but there are considerable differences in emphasis. Discussions include what design or certification problems are being addressed and why simulation methods (rather than direct evaluation using flight hardware, full scale components, or actual flight conditions) are employed. There is discussion of how simulation tools are used, what information is obtained from their use, and what criteria are used to evaluate their output. There is some discussion of limitations of current tools and of gaps arising from differences between simulation requirements and the current capabilities.

The article concerning the general aviation, business jet, and commuter aircraft industries provides valuable detail on the use of icing simulation capability in design and certification, as well as limitations and gaps in the existing capability. The large commercial transport contribution provides considerably less detail as to design and certification practice, but does provide a useful overview as well as valuable recommendations. The contributions representing the rotorcraft industry, the aircraft engines industry, and the ice protection industry also provide useful information and recommendations.

Providers and developers contributed articles including summaries of the capabilities currently available in their respective areas. Most contributions conform to some degree to general guidelines that were established for the user contributions, but there are considerable differences in emphasis. Discussions reflect the state of the art for the simulation method being addressed. Although it is not the intent to provide details for a particular facility, there is a tendency for the

articles to illustrate the state of the art through discussion of a premier government facility. Some discussion is included of design or certification requirements that can be met through use of a particular type of facility. There is some discussion of issues such as range of capabilities, accuracy, repeatability, and ease of use, and also of limitations of the simulation methods in terms of how well they function with respect to their stated purpose and how well they simulate natural icing encounters.

The icing tunnel contribution provides a comprehensive, detailed discussion of the state of the art for icing tunnels. It does not include a comprehensive survey of available facilities, but refers the reader to a report, where such a survey is available. The icing tanker contribution is not so detailed with respect to the state of the art, but does include a valuable survey of current facilities. The climactic chamber contribution is similar to that for icing tankers, also including a valuable survey of current facilities. There is no contribution for the very important and active area of analytical codes. However, the reader is referred to the very informative article "Review, Validation and Extension of Ice Accretion Prediction Codes" in Ice Accretion Simulation (AGARD Advisory Report 344, December 1977), which also includes an extensive list of references.

A table summarizing gaps noted by different industry users, and recommendations for improvement, is included in appendix C to this report. Examination of the table reveals several major concerns. One such concern is the development of criteria and validation data, as necessary, for acceptance of simulation tools in certification. A large number of recommendations are listed for icing analysis computer codes. Increased use of these codes is attractive to industry in part because of their potential for improvements in cost/flow time in the design and certification processes. Issues of validation data and acceptance criteria are recognized as especially relevant to icing analysis computer codes.

USE OF ICING SIMULATION TOOLS IN DESIGN AND CERTIFICATION

General Aviation Aircraft, Business Jets, and
Commuter Aircraft

Paul Olsen, Gulfstream Aerospace Corp.
Dennis Wariner, Cessna Aircraft Company

INTRODUCTION

Description of Aircraft in This Category

The following discussion is limited to the commuter, corporate, and general aviation aircraft classes. Commuter and corporate aircraft include the definition of the commuter class provided under 14 Code of Federal Regulations (CFR), Part 23.3: "propeller-driven, multiengine airplanes that have a seating configuration excluding pilot seats, of 19 or less, and a maximum certificated takeoff weight of 19,000 pounds or less," as well as smaller jet transport category aircraft certifiable under 14 CFR Part 25 with takeoff weights typically less than about 100,000 lbs. Most general aviation aircraft can be defined within the 14 CFR Part 23 Normal Category, limited to nine or fewer seats, excluding pilot seats, and maximum takeoff gross weights of 12,500 pounds.

Flight Operations of Aircraft in This Category

Unlike large commercial transports, the aircraft contained in this segment of aviation operate in vastly different flight regimes and have large variations in basic geometry characteristics. Cruise airspeeds from 100 knots to Mach 0.92, service ceilings from under 10,000 to 51,000 feet, and ranges from a few hundred nautical miles (nm) to nearly 7000 nm are possible. Flight into known icing (FIKI) is generally the domain of the higher-performance general aviation aircraft and standard commuter and business aircraft.

The size differences between commercial transports and the range of aircraft being discussed in this article have two consequences. First, although the business jets tend to fly at speeds and altitudes similar to the larger transports, their size allows them to access many airports from which larger aircraft are restricted. Smaller general aviation (GA) aircraft can use airports that the business jets cannot use. The result is flight into locations that may not have adequate facilities to forecast, identify, or deal with icing, or to relay that information efficiently to pilots.

Second, large commercial transports can accrete ice that is insignificant to them because of their size, yet the same thickness of ice on business jets or smaller GA aircraft can be especially dangerous. The size of the larger transports also helps them in other ways; their large blunt leading edges typically have lower collection efficiencies than the wing sections used on commuter, business jets, and smaller aircraft. Smaller aircraft, with their greater need to remove ice, ironically are subject to greater performance impact as a result of incorporating systems to address ice protection. Minimizing system weights and optimizing the system performance of ice protection systems become especially

important drivers for utilizing simulation methods in the design processes for business jets and GA aircraft.

Icing Certification of Aircraft in This Category

Flight into icing certification requirements have been set by various international certification authorities. In the United States, 14 CFR Parts 23 and 25 are applicable to the aircraft categories of interest. Ice protection requirements thereunder focus on operational safety of the aircraft in icing conditions defined in Appendix C of 14 CFR Part 25. These conditions serve in the selection of design points for ice protection systems and for unprotected iced surfaces. While design icing analyses can be used to show compliance with the pertinent regulations, ground and flight testing is also required. The following discussion will focus separately on icing simulation requirements as they pertain to both design and subsequent certification efforts.

ICING DESIGN REQUIREMENTS

Preliminary Design

Comparison of Envelopes and Preliminary Critical Conditions

The designer of an aircraft or aircraft component first needs to characterize the design's exposure to icing conditions. This is accomplished by comparing the flight envelope and mission profile information to the 14 CFR Part 25, Appendix C envelopes for continuous and intermittent maximum conditions. Critical icing conditions used in preliminary design can be derived from the exposures that generate the maximum ice accretions. Because of their size, these ice accretions tend to cause the largest airflow separation. In the preliminary design phase, maximum ice accretions are usually determined from analysis of exposure time, expected collection efficiency, exposed area, cloud liquid water content, and aircraft velocity.

Icing Zones

The designer's focus then turns to the aircraft components and their individual icing exposure. The designer must determine the zones where water droplet impingement will lead to ice accretion. This analysis is sometimes performed with one of the computer codes, LEWICE-2D, LEWI3DGR, or the three-dimensional (3D) impingement analysis code (ICE), available from Analytical Methods.

Tanker flights can also provide this information for modification work to existing aircraft or for designs that will be certified using arguments of similitude. An existing aircraft can be used if the test is on a mod, or a similar aircraft can be used if the test is on a derivative. (Tanker flights are also very valuable for icing research on new configurations at a later stage in the process.) Tanker flights can be used effectively to identify areas of high collection efficiency around new wing-body fairings and system scoop or vent designs. It safely permits local regions to be exposed without subjecting the entire airframe to potentially hazardous conditions in early stages of icing investigations, where performance and handling characteristics with ice are not well known. Components which experience impingement and accretion and so require ice protection systems are thus identified.

These computer predictions or tests influence preliminary decisions regarding parameters such as engine selection and aircraft weight and greatly impact the ice protection system selection. The results of the predictions or tests are used in determining power requirements, extent of protection, and use of deice vs anti-ice, which in turn can drive the designer with regards to selection of electrical, pneumatic, or engine-bleed protection systems. Accretions that occur forward of engines and blocked cooling scoops that require attention may be identified in early design stages. Unprotected subsystems such as antennas, probes, radomes, and fairings can be relocated, if so desired, to avoid ice accretion based on the icing zone information.

Detailed Component Design

Introduction

Icing analyses of aircraft components during the design phase are concerned with the determination of ice collection information for performance, shedding, and deicing/anti-icing design considerations. In particular, the designer must determine

1. Water droplet impingement limits
2. Collection efficiency
3. Water catch amounts
4. Ice accretion size and shape
5. Ice character/type (rime, glaze, mixed)

for the following operating conditions

1. Inadvertent encounters that are established based on the total time estimated for recognition and system activation (usually 3- to 5-minute shapes)
2. Intercycle shapes (based on the periodic activation time of mechanical/electrical systems)
3. System failures (typically 22.5 to 25 minute shapes)
4. Unprotected areas (based on the 45-minute holding criteria)

Airfoil Design

Historically, new airfoil designs have been driven by a desire to achieve certain characteristics of lift, drag, and pitching moment to meet design goals. However, because of icing concerns, new airfoil sections are now also routinely inspected for impingement limits, and have occasionally been redesigned because of the results. This additional airfoil design analysis is especially important for horizontal tails in this aviation segment because of the relatively thin sections employed.

General Exposed Surfaces

As other airframe components such as windshields, wing/body fairings, noses, radomes, and nacelles take shape, they are inspected for potential ice accretion, often with LEWI3DGR or the ICE code. Areas identified as accreting ice are examined for potential shedding hazards to the engine or airframe which would necessitate protection of the area (discussed below); otherwise they are classified as unprotected areas which will require simulated ice shapes for testing (discussed under Certification).

Ice Protection System Design

Introduction

If an ice protection system is required, the designer must do a separate heat-transfer analysis or mechanical deicing analysis, and information described below, in addition to collection efficiencies and water catch rates, must be determined.

Pneumatic Deicing Boots

For areas protected with pneumatic boots, the additional information involves an examination of the final loft contours, with an analysis code to make sure the coverage is appropriate. (The loft is the definition of the surface, typically a file, or a paper drawing.)

Electrical Deicing/Anti-Icing

For the areas protected with electrical heating, calculated collection efficiencies, water catch rates, and available electrical power are routinely shared with vendors who engineer the protection systems. Heat transfer coefficients must be established for heat transfer through the conductive surface and to the ambient air. Established methods such as V.H. Gray's graphical heat transfer solution in NACA TN-2799 (1952), outlined in the FAA icing handbook, provide heating requirements that can be conveyed to electrical system vendors.

Bleed Air Systems

For thermal systems which employ engine bleed air, designs often proceed using proprietary in-house analytical skin temperature heat balance models. Required inputs to these codes include bleed-air temperature, pressure, mass flow, system geometry characteristics, and heat transfer coefficients to balance actual heat delivered to the protected surface against measured results.

The heat transfer coefficients include both internal and external convective coefficients as well as 3D conductive coefficients through layered surfaces. Often these coefficients cannot be determined analytically. A specific example of such a code, developed and used by Cessna, is a heat balance code that predicts surface temperatures from known energy inputs. It uses an empirical data matching technique which necessitates first flying an instrumented system in dry air to calibrate results against measured surface temperatures. After conservative matches are performed, the instrumented aircraft obtains data from icing flights behind a tanker and in natural conditions to correlate with appropriate results for certification. Validation allows predictions extrapolated to icing envelope corner points to be used with confidence.

Runback Icing

Under certain circumstances, running wet systems are susceptible to runback ice formation. In these situations, runback amounts must be determined and runback ice shapes characterized. Fully evaporative systems spare the designer the need to worry about runback.

Impact of Icing on Performance

Component Systems Performance

Component systems such as probes, antennas, fairings, radomes, and the like may be degraded in performance by ice accumulation. Component performance impact studies must be performed to ascertain whether de- or anti-icing is required to maintain required system performance levels even when protection is not required by aircraft performance concerns.

Aircraft Performance

Aircraft performance impact begins with an ice drag estimate. Ice shapes and sizes must be well established to proceed. Analytical drag estimates are performed in accordance with procedures presented in "Engineering Summary of Airframe Icing Technical Data" (Report Number: FAA ADS-4), and the more recent "Aircraft Icing Handbook," Volumes 1-3 (Report Number: DOT/FAA/CT-88/8-1,2,3). Calculations are based on predictions of the volume of accreted ice. The results have been shown by check climbs to be very conservative because of conservative methods used to account for antennas, scoops, and other excrescences. Drag values are eventually validated in later testing through the use of check climbs. The check climbs are performed in back-to-back tests, with and without the artificial shapes installed. The climb gradients are measured and compared to gradient decrements computed in performance codes for the expected drag increment. The FAA also uses check climbs to confirm airplane performance.

Runback ice and intercycle ice (on deiced surfaces) must also be considered during performance impact analysis because of the critical surfaces on which these ice accretions form.

Knowledge of ice shape, size, and location are critical for predicting performance impact. Analytical methods are limited chiefly to drag prediction and to some extent maximum lift loss through the newer two-dimensional (2D) Navier/Stokes codes. The remaining aircraft performance attributes are most often evaluated in the postdesign phase through flight testing, although several items such as aileron hinge moments and tailplane stall issues might be tested in the tunnel before design lines have been frozen because of significant difficulties that have been encountered in late redesigns. Performance characteristics often evaluated in flight are wing stall, tailplane stall, drag polar increments, climb performance degradation, controllability and maneuverability, minimum control speed, and trim capability.

Shed Ice

Unprotected and deiced surfaces that collect ice must be assumed to shed at certain times. Runback ice behind protected surfaces can also build up into substantial shapes. Often, shed ice concerns are the sole reason for certain anti/deicing system installations such as those located upstream of inlets or critical structure. Requirements obviously begin with ice accretion prediction, either analytically, or with tunnels or tankers. Good ice shedding simulation requires a number of capabilities including:

1. Prediction of shedding events
2. Prediction of fragmentation

3. Characterization of fragment sizes and shapes
4. Identification of fragment trajectories
5. Determination of downstream impacts

Impacts must be analyzed for their effects on critical structure, noncritical structure, probe/antenna/radome components, and engine ingestion. Impact information on many of these items, be it from bird strike testing or engine ice ingestion testing, often has been recorded as part of the certification process. This reduces the shed ice impact problem to the identification of ice impacts that exceed the certified levels established for these aircraft components. In cases where shed ice trajectories are viewed as nonhazardous, tanker flights can be used to validate shedding predictions.

General Requirements for Icing Simulation Tools

The simulation methods used during design must be sufficiently flexible to accommodate what could be large numbers of geometry perturbations in the iterative design cycle. The nature of the aircraft industry is such that designs are completed by overworked staff working to tight deadlines and strict budgets. Low cost, quick turnaround times, and ease of use are therefore critical attributes for design icing simulation tools. Ideally there should be no loss of accuracy to meet these goals. If compromises must be made, they should not preclude design simulation results from being used to support certification reports. The intention should be to provide both design guidance and a basis for future certification, eliminating any need for a duplicate effort.

Industry needs codes that are useful as design codes and also accepted by the FAA for producing analyses to be used in certification reports. An example of duplicate effort would be using a simple and fast code with limited accuracy to do a design, and then checking out the results in a slow, difficult, but "validated" code for certification.

Impingement limits are customarily run for new airfoil designs to assure they will not require extensive ice protection coverage. Analysis is run months later to size protection systems accurately for specific flight conditions. Frequently in certification programs, several more cases are investigated to address specific conditions.

Ice shape definition has characteristically followed a similar path in recent years. Current 2D methods have been robust enough to keep pace with these demands up to now, but as simulation requirements are pushed, similar response will be requested from higher order 3D methods.

CERTIFICATION REQUIREMENTS

The Role of Simulation Tools in Certification

The continuous increase in icing awareness and the broader interpretation of existing regulations has created an even greater dependency on simulation tools for icing certification for general aviation. FAA/JAA harmonization efforts that were to simplify certifications have often become a vehicle through which each authority has increased related requirements. Rather than fewer flight tests, more are now required to test an increasingly large array of simulated ice shapes and to satisfy natural icing flight test requirements.

Tests are even being conducted with shapes that have never been shown to accrete on particular configurations. Because certain aircraft have been shown to accrete particular shapes and to experience problems with those shapes, it is now required that it be assumed that entire classes of aircraft can accrete similar shapes. Thus, entire classes of aircraft must be tested with those shapes. Simulation methods are needed that can reliably predict unique shapes for specific aircraft and identify the specific cases in which they occur. If simulation methods were sufficiently reliable, and they showed that some of the ice shapes do not actually occur on some of the designs, testing requirements could be reduced with no adverse impact on safety. Manufacturers could use the methods to improve their protection systems, prove the adequacy of their designs, or simulate shapes applicable to their configuration.

Regulatory Requirements

Aircraft certification requirements for flight into known icing can be divided into certification of protected surfaces and unprotected surfaces. Protected surfaces require validation of the protection system in addition to the basic icing analysis. Unprotected surfaces require a substantial investment in flight testing to prove that operation of the aircraft with ice-contaminated surfaces is safe over the affected envelope.

The FAA requires that several tests be conducted for certification. Some of these tests can make use of simulation tools and facilities, although some natural atmospheric icing testing is always required. The remaining tests can include:

1. Laboratory (not necessarily tunnel) dry air or simulated icing tests
2. Flight tests in dry air of the ice protection system
3. Flight tests of the aircraft in measured simulated icing conditions

Protected Surfaces

The basis for the de- or anti-icing system design must be presented to the certifying authority, hence, the requirements for icing simulation tools listed under "ice protection system design" are the same for certification. In contrast, the requirements for validation of system performance extend into flight testing and areas well beyond those explored during initial design.

Ice protection system parameters utilized during system design must be validated during performance testing or through ground lab tests and dry air flight tests (tests 1 and 2 above). Ground laboratory tests, not necessarily tunnel tests, have been used to measure the performance of electrical resistance heating and to determine certain internal parameters in bleed-heated systems. Laboratory and flight dry air testing are used to determine the remaining temperature, pressure, mass flow, and coefficient data.

System performance must be validated for certification. The design heat-transfer rates must be achieved, and the heat transfer must be adequate for de- or anti-icing. Electrical system heat-transfer rates can be tested in icing tunnels with less difficulty than engine bleed systems, which are more typically validated via natural icing flight testing or tanker testing. Adequacy of the proven rates is shown through natural icing and simulated icing in tunnels or behind tankers. In all of these efforts, the goal of testing is to prove the adequacy of ice protection, beginning with detection of ice either visually (day or night)

or with the aid of automated ice detectors and concluding with the elimination of accreted ice and/or prevention of new accretion.

Runback ice that forms behind running-wet surfaces can have a significant performance impact. Runback must be investigated, the ice shapes determined, and flight tested. The current state of technology prevents the determination of runback shapes using computer simulations. Tunnel data is sparse and of limited applicability. The caprice of natural conditions limits the usefulness of natural ice flight testing to fully investigate runback. Only tanker flights serve to seriously investigate runback. As some of the tankers used in industry put out quite a lot of large droplets, tankers are regarded as a rather conservative tool for the determination of runback shapes, at least as far as their size is concerned. The resulting shapes are measured, modeled, and tested in the artificial shape flight test phase for unprotected surfaces.

Unprotected Surfaces

Performance impact of ice shapes forming on unprotected surfaces should have been predicted during component design, since they must be considered for their contribution to total drag and can frequently impact some system's performance. Certification requires flight test of ice shapes to validate that accumulation of ice on unprotected surfaces and behind protected surfaces does not render flight operations unsafe.

To obtain controlled, measurable ice accumulations, artificial ice shapes are most often used. These are usually 45-minute-hold shapes and must be determined accurately and reliably by means of analysis, tunnel tests, tanker tests, or natural flight tests. For those companies with access to a tanker, unprotected regions are cataloged early and their attendant shapes documented from actual ice accretions. For tankers with large droplets in their spray, this is probably conservative as to the size and impingement limits. Unacceptable accretions are thus quickly identified and protection system performance optimized.

A tanker, such as the one currently employed by Cessna, that uses a fixed nozzle size and a small spray boom creates a focused plume that requires individual parts of the aircraft to be examined independently. This may appear to be a hindrance because only a small portion of the aircraft may be examined at a time. However, a significant attribute of this "targeted testing" is safety. Individual parts of the aircraft are thoroughly examined before subjecting an entire airplane to icing.

Another great advantage of the tanker for simulated shape testing comes in regard to developing runback ice shapes, where analytical codes currently have no predictive capabilities. Icing tunnels are also used when analytical methods cannot be applied. Nonetheless, the advantages of icing codes over the testing, namely low cost and speed and simplicity of execution, are significant, provided the codes are employed within their limits of accuracy. Shapes developed in the codes can also be quickly converted to templates for fabrication of scab-on shapes. All artificial shapes, regardless of origin, simulate the mass, size, shape, and surface roughness of expected critical ice accumulations under 14 CFR Part 25, Appendix C conditions.

Artificial shapes must be flight tested on the full-scale aircraft and also may be tested on models. Testing is conducted to gauge impact on aircraft performance parameters listed

earlier under "Design Requirements, Icing Performance Impact." Flight testing is most versatile for these requirements, and is preferred by the FAA. Maneuvers such as check climbs are conducted to extract pertinent drag data. Other aircraft performance is evaluated with the appropriate simulated shapes installed for each test. For example, tailplane stall margin is tested with several ice shape configurations; sandpaper and simulated intercycle shapes are the most common for these zero-g pushover tests. Controllability and maneuverability are stressed throughout all phases of ice shape testing. Performance of stall warning systems and air data computer systems are also tested with simulated shapes installed.

The final step in certification testing is natural atmospheric icing condition flight testing. Requirements here involve locating intermittent maximum and/or continuous maximum conditions, flying the test aircraft into said conditions and reliably measuring icing parameters once on station within the clouds. Ice protection equipment must be validated during the natural icing encountered, and unprotected surfaces must not accumulate ice that jeopardizes the safety of flight operations.

GAP ANALYSIS

Analytical Codes

Within industry some of the greatest needs are in the area of code development and improvements. Changing certification requirements have added what some aircraft manufacturers believe may be unnecessary burdens to icing certification programs. For example, some aircraft manufacturers are being required to test shapes that have not been found to accrete on their aircraft. These requirements were instituted because other aircraft in the same class but with dissimilar airfoils and configurations accreted particularly hazardous shapes. These and other tests add even more costs to already expensive icing programs.

Codes that could predict these shapes, including for supercooled large droplet (SLD) conditions, would help determine if similar shapes are necessary for testing. The ability of analytical codes to reduce costs and return results in a timely fashion, coupled with the ever-increasing speed and power of computer processing, strongly suggests that significant achievements are possible through application of developmental resources to analytical ice prediction codes.

Analytical Code Applications

Analytical codes hold great promise for design work because of features that include quick turnaround, low cost, simple perturbation of surface geometry, and the minimal involvement of corporate resources beyond a computer workstation and an educated user. Predictions of ice accumulation are useful also in certification, when artificial shapes are constructed and ice protection validation is conducted. The roles of analytical codes envisioned include:

1. Preliminary design: determination of impingement zones
2. Detailed design: determination of impingement limits, collection efficiency, water catch, ice accretion size, shape, and location

3. Ice protection system design: heat transfer coefficients, water catch, runback water, runback ice shape size, and location

4. Shed ice: shed prediction, ice breakup, fragment trajectories

5. Certification: artificial ice shape generation

Current Strengths

Excellent features which are found in some of today's codes and which must be retained include:

- Capability to determine basic icing parameters, such as impingement limits
- Applicability to arbitrary configurations (including lifting and nonlifting surfaces)
- 2D and 3D capability
- Repeatability of results
- Low cost for code acquisition
- Low cost for code use
- Simple modeling with easy surface perturbation for design iteration/reanalysis
- Quick turnaround
- Applicability to general configurations (not limited to lifting surfaces and their leading edges)

Desired Improvements

The tasks listed require capabilities that are not fully developed in today's codes. Desired features include

- Validation satisfactory for FAA acceptance of code results
- True 3D capability (e.g., current LEWI3DGR code calculates ice accretions on 2D regions of interest only)
- 2D codes should work with nonlifting, nonairfoil shaped geometry
- Large droplet capability
- System modeling to include:
  - Clearing of ice periodically on mechanically protected regions
  - Runback, incorporating heat transfer outputs from ice protection system codes.
- Accurate water catch prediction
- Accurate ice shape, size, and location prediction.
- Ice shape growth with shape/flowfield iteration, where the flowfield is recalculated to include the presence of the accumulating ice shape
- Good rime, mixed, glaze modeling at appropriate temperatures
- Short user spoolup/simple training for code users

- Ease of use
- Robust operation (output sensitivity to time step and some other inputs is one concern)

The desire to achieve codes whose analyses are admissible to regulatory agencies in support of certification for a design should not result in a colossal effort being spent to produce just one "certified" code. The generation of a validation database would more directly suit the purposes whereby many codes could prove the accuracy of their results for certification purposes, leaving the designer free to choose the tool that most suits his needs for each particular design.

A final comment, which looks beyond the ice accretion problem but remains within the application of accretion codes, involves ice protection system design. If analysis codes were capable of modeling proposed ice protection system operation in conjunction with ice accretion, the combined tool would be exercised in early design stages to avoid incorporating inadequate protection or airfoil shapes that result in the formation of especially hazardous shapes like beak ice. These codes would also be very valuable in evaluating existing configurations and examining their potential ice shapes. This would help manufacturers identify particularly poor configurations or provide evidence that designs are adequate and thus avoid costly testing irrelevant to their configuration.

Icing Tunnels

Icing tunnels allow the strict control of icing parameters for detailed investigation of icing phenomena related to design and certification of aircraft. The cost and scheduling requirements of tunnels, combined with their limited numbers across the country, preclude their use in everyday design work. Like tankers, their value is due to the accuracy of results, and they are particularly useful during checkout of designs, investigation of problems, and certification, similar in many senses to the modern use of wind tunnels in the age of computational fluid dynamics (CFD).

Icing Tunnel Applications

During the design phase, tunnels are useful in determining component ice accretion including ice shape, size, location, and roughness, as well as troubleshooting problem areas. Tunnels are also needed to validate the results of icing codes on which certification efforts are based. Other certification roles involve ice protection system validation, artificial shape generation, aircraft performance testing, and investigation of unexpected/problem ice accumulations.

Icing Tunnel Strengths

Some of the important strengths from the manufacturers' viewpoint for design and certification are:

- Repeatability
- High degree of control of test conditions
- Costs less than flight testing in natural icing conditions
- Year round availability

Desired Improvements

The most significant desired improvements for tunnels are expansions of simulated conditions.

- Increased 14 CFR Part 25, Appendix C coverage
- SLD capability, including freezing drizzle and freezing rain.

Icing Tankers

While there is currently no substitute for testing in natural icing encounters, icing tankers provide the nearest simulation of icing on full-scale aircraft in realistic flight conditions.

Icing Tanker Applications

In preliminary design, tankers are valuable in the determination of impingement zones.

For detailed design, tankers aid in the determination of impingement limits and ice accumulation, including runback and investigation of ice protection systems. During certification, tankers are valuable for ice protection system validation, evaluation of unprotected surface icing, and simulated shape generation.

Icing Tanker Strengths

- Validation as well as evaluation of designs
- Full-scale simulation
- Year-round availability of icing conditions
- Selected exposure areas

Desired Improvements

- Availability
- Greater spray coverage when needed
- Greater repeatability—Finding the same environmental conditions is difficult on different flights. Pilot technique dictates how a test airplane sets within the spray plume and the relative positions of tanker and test aircraft determine specific icing conditions established. Because of the cold and clear conditions sought for tanker testing, the plume will dissipate very quickly in the high, nonhumid conditions. Icing conditions defined by liquid water content (LWC) and droplet size will vary rapidly with distance from the tanker aircraft. For this reason, it is absolutely necessary to instrument the test aircraft with appropriate icing probes. Variable nozzles used on the Air Force tankers provide considerable flexibility, but for tankers with fixed nozzles, the lesser flexibility can be overcome with diligent efforts.
- Reasonable cost—The major limitation to the use of tankers is their availability. Certain jet-powered commuter and corporate aircraft are currently without tanker capability at suitable airspeeds and altitudes. Other tankers such as the Cessna tanker have been offered on a limited availability basis. Ideally, a tanker fleet would be available that could cover the entire regime of flight from general aviation FIKI aircraft up to large commuter and corporate jets. Spray quality would be strictly controlled and results repeatable. Spray coverage would be as extensive as possible

to best simulate full 3D effects. Costs would be reasonable to the extent that manufacturer support of the tanker programs would be encouraged, while internal costs are held low to enable the programs to be self-sustaining.

Climatic Lab Facilities

The authors of this section have no experience with climatic labs or their application to design or certification for FIKI. They have been used primarily for ground icing, not in-flight testing.

CONCLUSION

The design and certification of commuter, corporate, and general aviation aircraft for flight into known icing has been greatly simplified by the available icing simulation tools. There is a good deal of work that still remains to be done, however, including improvements that will aid in enhancing aircraft safety by putting more powerful tools in the hands of aircraft designers and certification teams.

The design of aircraft components for flight into known icing requires low cost simulations that provide accurate results quickly and easily for the designer. The time and cost involved with tunnel models and flight test limits the designer to computational simulations for the most part. Current codes are very useful but the accuracy of their results must be improved. Ice growth must be modeled realistically, with accreted shape/flow field iteration. Three-dimensional effects need to be understood and modeled, complex heat transfer and 3D problems such as runback ice addressed, and ice shedding included.

Icing tunnels are often used to verify designs and code predictions and to indicate potential trouble areas that may have been overlooked. More validation work should be done, perhaps in the form of a collected validation database for the icing codes. Expansion of tunnel test conditions is also desirable in order to keep up with the changes in regulatory requirements. Tankers serve many of the same purposes as the tunnels, although they require flying prototype fabrication that is costly in the design phase. For certification they offer the great advantage of excellent full-scale simulation of natural conditions. Unfortunately, icing tanker availability is next to nil except in limited cases, which completely undermines their strengths to aircraft manufacturers.

Certification is accomplished through testing, having not yet reached the point where computational simulations are adequate to certify components except to establish those locations not subject to icing. Testing in tunnels serves as an investigative tool, providing artificial shapes for unprotected surfaces. Flight test provides most of the validation required. Dry air, tanker, and natural atmospheric flight testing are conducted with artificial and natural shapes to validate ice protection schemes and demonstrate safe flight with simulated shapes on unprotected surfaces. The rarity of tankers limits their role in most certifications, where they could be very useful to address the highly focused problem zones that are often encountered during certification flight testing.

In conclusion, the need for improvements in icing simulation tools, which have the potential for a positive impact on certification, must be stressed. One direct result of improved tools will be the enhanced safety of flight into known icing conditions.

Additional benefits include reduced certification and design costs, better designed aircraft, and higher confidence levels in industry and in the FAA regarding the accuracy of methodologies employed to satisfy the flight safety requirements.

USE OF ICING SIMULATION TOOLS IN DESIGN AND CERTIFICATION

Large Commercial Transport Aircraft

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SIMULATION REQUIREMENTS

Icing simulation methods are used in both the design and certification of large commercial jet transports. These methods are part of the design and validation process which proves that (1) the ice protection system performs as intended and (2) the effects of ice accretion with a normally operating ice protection system are as predicted.

The design of thermal ice protection systems use both icing wind tunnels and computer codes. For large commercial jet transports, portions of the wing leading edge, the nacelle leading edge, and in some cases, the horizontal tail leading edge are protected with thermal systems. Icing wind tunnels and analyses with computer codes are used to design these ice protections systems. The design of these thermal systems requires analyses of the total system's ability to provide heat energy to protect the above-mentioned leading edges in the applicant's design standard—typically the continuous maximum and intermittent maximum icing conditions of 14 Code of Federal Regulations (CFR) Part 25, Appendix C. The computer codes and analyses determine heat energy required for the protected surfaces at the worst case condition of the flight and the design standard envelope. The icing tunnel tests are used to evaluate components of the design, and are a valuable tool expediting redesign if the initial ice protection performance is not adequate.

With respect to certification, icing simulation codes are used to define the critical ice shapes (as required by 14 CFR Part 25, Appendix C and associated guidance material) and the heat energy requirements for the protected surfaces. The simulation codes and analyses determine the critical ice shapes as a function of the flight conditions (e.g., airplane configuration, speed, angle of attack, attitude, and exposure time) and the icing conditions of Appendix C (temperature, liquid water content, and median volume diameter). The critical ice shapes are modeled on wind tunnel models and the flight test airplane to evaluate the change in aerodynamic performance and handling characteristics. The analyses of the results of dry air wind tunnel testing of these models with artificial ice shapes are used to substantiate the predicted performance and handling characteristics. Flight testing with artificial ice shapes provides further validation of these predicted airplane performance and handling characteristics.

Icing simulation methods, icing wind tunnels, and codes are used to analyze the performance of the ice protection system and to determine that the protection for the various components of the airplane is adequate for the various operational conditions within 14 CFR Part 25, Appendix C icing conditions. In most cases, to verify this ice protection analysis, to check for anomalies, and to demonstrate that the ice protection system and its components perform as intended, the airplane and its components are

flight tested in various operational configurations in measured natural atmospheric icing conditions.

CURRENT SIMULATION CAPABILITIES

Icing wind tunnels provide a controlled and repeatable icing environment for the generation of ice shapes on airfoils, wings, bodies, propulsion systems, and other components. These facilities are used to simulate 14 CFR Part 25, Appendix C and some "estimated" supercooled large droplet (SLD) icing conditions. In most cases, the flight operational conditions are simulations of true flight situations. Ram air turbines (RATs), air intakes, antennas, radomes, and air data sensors are evaluated for their ice accretion characteristics. Two-dimensional airfoils or truncated models are used to provide the largest possible scale, which results in only a "section cut" simulating a portion of a wing or empennage; this is done to maximize the droplet size to icing surface scale ratio, which is a powerful variable. For the evaluation of ice protections systems, wing leading edge systems are simulated on scaled or truncated airfoils, whereas for nacelle inlets, very large scale models of the nacelle leading edge ice protection systems are tested in these tunnels.

Most icing wind tunnels are atmospheric, low speed facilities with maximum velocities ranging from 150 to 350 kts and a temperature range of –25° to +32°F. The water content of the air can be varied from about 0.2 to 3.0 g/m^3, and with droplet size variation of 15 to 40 microns. Data correction values are generated by calibrating each installation (which is standard wind tunnel practice).

As an example, the Boeing Research Aerodynamics and Icing Tunnel (BRAIT) was calibrated in two phases. The first phase concentrated on the determination of the basic flow qualities of the clear tunnel in the dry mode without water injection. The second phase determined the calibration of the icing conditions. The calibration was made at the center plane of the test section, and the following flow parameters were determined:

1. centerline static pressure correction,
2. velocity uniformity,
3. turbulence intensity distribution,
4. temperature uniformity,
5. clear tunnel upflow and crossflow, and
6. wall boundary layer thickness.

The second phase icing condition calibration was conducted by cooling the air to 0°F and injecting water droplets into the airstream via the spray bar system to simulate natural icing conditions encountered during flight. The calibration determined the following:

1. individual nozzle calibrations,
2. droplet size calibration,
3. cloud uniformity, and
4. liquid water content.

LIMITATION OF CURRENT SIMULATION METHODS

The one major limitation of our current simulation methods is the lack of standards or criteria to judge the acceptability of ice accretion simulation methods. This is true for simulation codes, wind tunnels, tankers, and environmental test chambers.

In most cases, icing wind tunnels like the BRAIT have been well calibrated (as discussed in the previous section). The one possible missing test section characteristic is the turbulence level of the flow with the water spray on. In the past, the instrumentation and methods to measure the turbulence levels with water droplets were not available; however, very recent research has demonstrated the ability to measure this characteristic. The icing research community has not yet determined the importance of the measurement of test section turbulence levels.

Because of the presence of the water droplet spray system as well as the heat exchanger necessary to bring the airstream temperature down to levels conducive to icing, the turbulence levels in these icing simulations are generally higher (sometimes by an order of magnitude) than aerodynamic wind tunnels. Currently we do not have detailed knowledge of prevailing turbulence intensities in natural icing clouds, so the proper simulation of the icing environment is in question. This issue does not appear to pose a major limitation on simulating a natural environment for simple geometries, where ice accretion is primarily a leading edge event. For complex geometries, such as multielement airfoils where ice accretion has been observed on the downstream elements as well as on the slat, the accuracy of these accretions comes into question.

Another issue that hampers our understanding of the icing wind tunnel results is the droplet scaling. Exact duplication of an aircraft in natural icing conditions cannot be accomplished due to the various icing tunnel limitations. Typically, flight velocities are higher than the maximum tunnel velocity capability; the tunnel has a limited range of cloud liquid water content capability that does not extend as low as flight conditions; and icing tunnels are atmospheric facilities which are limited to near-sea-level pressure conditions. (This is an important factor in evaporation rates and simulating high altitude conditions.) This combination is a particularly unfortunate limitation when simulating high speed, low liquid water, high altitude cloud conditions.

To compensate for these limitations, various thermodynamic scaling and similarity laws have been developed. The methods use thermodynamic equations to determine how to vary tunnel parameters to maximize the similarity between flight and tunnel test conditions. As in aerodynamic wind tunnel testing, it is not possible to match all parameters, and judgement is used to determine which parameters are most important. The tunnel parameters that can be set to obtain similitude with flight in icing conditions include:

1. tunnel cloud liquid water content,
2. tunnel temperature,
3. tunnel velocity,
4. tunnel cloud median volume diameter (MVD),
5. model surface temperature,
6. tunnel run time, and
7. wind tunnel model and scale.

The tunnel pressure is not a parameter that can be controlled with the current atmospheric icing tunnels, and is assumed to be fixed at the local ambient atmospheric pressure. There have been many scaling methods developed to address this problem of testing methods in facilities with limitations in either model size or test conditions. These methods have all been based on a physical description of the ice accretion process with various assumptions and simplifications. The usual approach in developing a scaling method is to write expressions for the water droplet collection efficiency, total ice accretion on the surface, and an energy balance at the stagnation line of the airfoil. The scale and reference values of these expressions are equated to solve for the scale test conditions. Also, truncated/hybrid airfoils with full-size leading edges are used to allow the matching of droplet trajectory and surface impingement characteristics. This is important due to the limited ability to scale droplet MVD.

There are concerns that the droplet flow field in the icing wind tunnel is not being simulated adequately. The evidence for this has come from observations of ice accretion on flap lower surfaces in the icing wind tunnel. Observations from flight testing have been contradictory and have led some icing engineers to question other factors, such as the vertical velocity of droplets not being simulated properly in the icing wind tunnel.

There are no readily available pressure icing wind tunnels to simulate altitude effects and no high-pressure icing facilities to simulate Reynolds number effects. Whether these effects play a significant part in the ice accretion process has not been established.

Three-dimensional (3D) effects do have a significant effect on the ice accretion process; however, icing wind tunnel test sections are generally too small to test complete airplane configurations. Since the droplet size in the icing process is difficult to scale down, large models are generally desired.

GAP ANALYSIS

In order to understand that the total in-flight icing process is correctly simulated, the icing wind tunnel must correctly simulate the natural icing conditions and the aerodynamic flow field. Hence, icing wind tunnels will need to be calibrated for icing condition simulation as well as the aerodynamic flow qualities, and validated for ice shapes and their features. In order to use icing wind tunnel simulations for design and certification of aircraft, they must be able to produce the natural icing conditions of Appendix C of 14 CFR Part 25, and if determined critical, the new categories of SLD, freezing rain/drizzle, ice crystals, etc. The facility must also produce the operational flight characteristics for the icing environment; such as, aircraft configuration, flight speed, and flight lift/angle of attack which are representative of takeoff, en route, holding, and failed ice protection in holding and enroute conditions.

The calibration of the facility for icing conditions will require the determination of the water nozzle/spray bar system characteristics, the water droplet size/statistical distribution, uniformity of the droplet distribution across the test section, the MVD, and liquid water content. An unobtrusive droplet measurement system to set the icing test conditions would be very desirable. These icing condition characteristics must be representative of the natural icing conditions of Appendix C of 14 CFR Part 25, and, if critical, the new categories of icing.

Finally, the validation of the facility for the accuracy of ice shapes and their features for the variety of conditions and exposure times representative of the Appendix C of 14 CFR Part 25 envelope and airplane flight operations must be established. The aerodynamic flow quality calibration must include all the typical parameters required of high quality aerodynamic wind tunnels. These parameters include clear tunnel upflow/crossflow, turbulence levels with and without water injection, velocity and temperature uniformity, static pressure distribution on the test section centerline and along the walls, wall boundary layer characteristics, and wall interference/blockage with a model in the test section. The aerodynamic characteristics of the measurement system must be calibrated.

High Reynolds number icing wind tunnels are not available. The investment for a pressure icing facility would be enormous; hence, an analytic study of altitude and Reynolds number effects to determine the necessity for this type of facility might be a cost effective alternative. This approach probably should also be used to understand the necessity for icing facilities with complete 3D airplane configurations capability.

A summary of the known gaps in icing wind tunnel simulation methods is listed as follows:

- Standards/criteria for acceptance of icing wind tunnels for airplane certification.

Accuracy requirements for ice shape and features for airplane certification for flight in icing conditions for Appendix C of 14 CFR Part 25.

- Additional icing environment simulation capability beyond Appendix C of 14 CFR Part 25 as needed.
- Understanding droplet scaling effects.
- Understanding Reynolds number effects on ice accretion.
- Understanding low Reynolds number aerodynamic testing for ice effects on performance and handling characteristics.
- 3D ice accretion testing method.

IDENTIFICATION AND PRIORITIZATION OF FUTURE SIMULATION METHODS

The number one priority for the future requirements for icing wind tunnel facilities will be to meet the acceptability requirements of the airplane certification process for flight in icing conditions. The first step to accomplish this is to establish the standards/criteria for acceptability of the facility by the regulatory authorities. A key component of this future icing wind tunnel requirement is the knowledge of the accuracy of the ice shapes and features produced by these facilities, and the accuracy requirements for the determination of the aerodynamic performance and handling characteristics of ice.

Number two priority for icing wind tunnels is the capability to test for in-flight icing in three dimensions. To achieve this capability would require the understanding of droplet scaling and Reynolds number aerodynamic testing.

RECOMMENDATIONS FOR RESEARCH INVESTMENT STRATEGY

The recommendation for research investment strategy should be based on the needs of the airplane certification process for flight in icing conditions and the need for industry to reduce the cost/flow time of this certification process. All icing simulation methods must establish that they meet the standards/criteria for the acceptability of each method (codes, wind tunnel, tankers, and environment test chambers). Included in these acceptability criteria are the accuracy requirements of the ice shapes and their pertinent features affecting the airplane's aerodynamic performance. These requirements will then determine the technology needs. Research which will reduce cost/flow time must be high on the priority list.

USE OF ICING SIMULATION TOOLS IN DESIGN AND CERTIFICATION

Rotorcraft

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SIMULATION REQUIREMENTS

The testing of a rotorcraft to confirm the intended operation of an ice protection system in natural icing, whether the rotorcraft is a conventional helicopter or a tilt rotor aircraft, can be a very time consuming and expensive process. There are altitude and airspeed limitations inherent in the design of a helicopter and altitudes that characteristically have higher liquid water contents can not be reached. (Note that reference 1 defines a 10,000-foot altitude-limited certification envelope for helicopters.) In addition, the range and speed of a helicopter preclude flying quickly to distant locations that may have more suitable icing conditions on a given day. Tilt rotor aircraft have more flexibility in seeking icing conditions during a test or certification program, but a tilt rotor aircraft will still not have the advantages of a jet transport in flying quickly over a long distance to find a wider range of certification conditions. Due to the much more limited range of a typical helicopter, the test team has to wait for icing clouds to come into the vicinity of the flight test base.

These operational difficulties create a requirement for improved and accepted simulation methods, both codes and test procedures, to aid in the certification of rotorcraft for flight in icing. Table 1 shows where simulation methods are now used and how this is expected to change in future years.

TABLE 1. ROTORCRAFT INDUSTRY RELIANCE ON ICING SIMULATION TOOLS FOR QUALIFICATION AND CERTIFICATION

	CURRENT PRACTICE (THROUGH 1999)			FUTURE USE (2000 AND BEYOND)			REMARKS
TOOL	DESIGN	QUAL	CERT	DESIGN	QUAL	CERT	
THERMODYNAMIC AND AERODYNAMIC CODES							
SIMPLE THERMO. ANALYSIS	I			I			LIMITED USE
LEWICE 2D	I,R			I,R	I,R	I,R	CURRENT STANDARD
LEWICE 3D							NOT REQUIRED
LEWICE NS				R	R	R	FOR SEPARATED FLOWS
LEWICE ET				I,R	I,R	I,R	EXPAND USAGE
ROTOR PERF. STRIP ANALYSIS	R			R	R	R	LIMITED ACCEPTANCE NOW
FLIGHT SIMULATOR				R	R	R	NEED TO BEGIN USING
GROUND FACILITIES							
SMALL WIND TUNNELS (< 4 FT X 4 FT)							FOR INSTRUMENTS ONLY
LARGE WIND TUNNELS (BRAIT, IRT)	I	I	I	I,R	I	I	TOO SMALL FOR FULL-SCALE ROTORS
ENGINE TEST CELLS							NOT REQUIRED

TABLE 1. ROTORCRAFT INDUSTRY RELIANCE ON ICING SIMULATION TOOLS FOR QUALIFICATION AND CERTIFICATION (Continued)

	CURRENT PRACTICE (THROUGH 1999)			FUTURE USE (2000 AND BEYOND)			REMARKS
TOOL	DESIGN	QUAL	CERT	DESIGN	QUAL	CERT	
GROUND FACILITIES (continued)							
MCKINLEY CLIMATIC HANGAR		C	C	I,R	I,R	I,R	NEED TO EXPAND USE
NRC HOVER SPRAY RIG	R	I,R					OUT OF SERVICE
TANKERS							
HELICOPTER ICING SPRAY SYSTEM (HISS)	I,R	I,R		I,R	I,R	I,R	GIVES CONSERVATIVE RESULTS
SMALL FIXED WING TANKERS							CLOUD TOO SMALL
C-130 TANKER					I	I	SMALL CLOUD
KC-135 TANKER							FLIGHT SPEED TOO HIGH
OTHER							
NATURAL ICING TESTS		R	R		R	R	REDUCED RELIANCE >Y2000

Notes: R - Rotor Work
I - Inlet Work
C - Cold Environmental Test Only

The icing characteristics of a rotorcraft have many similarities to those of a fixed wing aircraft, but there are also many differences. The effects of icing on windshields, engines and engine inlets, and on instruments such as the airspeed system are similar to that for a fixed wing aircraft and, therefore, ice protection requirements will be similar for both types of aircraft. Tail surface icing may be less critical for a helicopter than a fixed wing aircraft, since there is considerable control power available from the rotors to aid in aircraft trim. The AH-64 Apache and UH-60 BLACK HAWK helicopters do not need tail surface ice protection, but the Super Puma/Cougar does require horizontal tail ice protection due to the particular geometry of its horizontal aerodynamic surfaces and the trim characteristics of that helicopter.

The effect of icing on a helicopter rotor is very different from the effect of icing on a wing. Also, a tilt rotor aircraft will experience helicopter icing characteristics while flying as an in-plane rotor, but the proprotor will have icing characteristics similar to a propeller when in a vertical orientation. A typical rotor blade has a high aspect ratio and three-dimensional effects are much less important than for an airplane wing. The blade angle of attack and local flow velocity change during each revolution of a helicopter blade in forward flight. The local airfoil angle of attack may vary from transonic, low angle of attack conditions at one instant of time, followed by low velocity, high angle of attack conditions when the blade is in the opposite azimuthal position. Therefore, the rotor blade may see large ranges in effective sweep angle during each blade revolution.

The type of ice normally varies along the span of a blade. Inboard icing may be rime ice, transitioning to glaze ice further out on the blade. Regions of beak ice (an ice accretion formed near the suction peak of an airfoil when the free stream total temperature is above freezing) and regions of no icing may exist simultaneously on the blade, depending on the

flight temperature and rotational speed. Centrifugal forces and vibratory forces play a significant role in both induced and natural ice shedding.

Current production rotorcraft use single-element airfoils, so multielement analyses are not needed. Researchers have concluded that the prediction of ice accretion can be reasonably represented by assuming average rotational velocities and average angles of attack for a given blade span location. Oscillating airfoil tests and model rotor tests have shown that the oscillating angles of attack create a smoother ice shape than a similar test with a static airfoil [2]. The simulation of icing conditions in general and of ice accretions in particular for rotorcraft has not achieved widespread acceptance by either the aircraft industry or qualification and certification authorities. The U.S. Army used the YCH-47 Helicopter Icing Spray System (HISS) to qualify the UH-60 and the AH-64 for flight within the icing environment defined by the Department of Defense (DoD). However, concern over the large size of droplets and the turbulence in the wake of the YCH-47 has limited the acceptance of the HISS, even though the larger droplets may cause greater performance penalties. The HISS cannot, in its current configuration, ice a complete helicopter due to the spray height. The HISS can provide a cloud that adequately ices a rotor with a diameter less than about 55 feet. Proposals to upgrade the HISS nozzles and spray bars have not been acted upon. Other tankers exist, but have limited usefulness due to flight speed requirements (the KC-135, for example, had a minimum flight speed higher than the speed for helicopter icing tests) and cloud size.

Limited testing has been done in the National Research Council of Canada's Helicopter Icing Spray Rig, but that facility, when it was operational, could only be used to evaluate accretion and deicer performance in very low speed conditions. The McKinley Laboratory Climatic Hangar could provide a good simulation of rotor icing, but the cloud liquid water content is currently too low and existing spray bars are too small to demonstrate "flight" in 14 CFR Part 29, Appendix C conditions. Further investigation into the capabilities of this facility and the validation of the facility is warranted.

Wind tunnel tests have been used to conduct research on rotary wing ice accretion and nonthermal deicing. However, this type of testing employs small-scale models and application of scaling relationships is a concern to some people. Information gathered using simple and complex models has produced valuable data. The range of controlled conditions available in an icing tunnel provides a means to explore the full icing envelope for a rotorcraft design. The analysis of existing model-scale rotor data acquired in the Icing Research Tunnel (IRT) in 1993 needs to be completed and the results published so that the information is available to support validation of scale model testing for use in certification.

Significant progress has been made in the usefulness of computer codes. LEWICE has matured significantly over the years and could become a very powerful tool for design and certification of rotorcraft, once some barriers are eliminated. Rotorcraft users of the code have been frustrated in repeating test cases from one computer platform to another and confidence in results for other cases is also a concern. Augmented user support is warranted, if LEWICE is going to become the industry standard. For the purpose of rotor ice accretion predictions, emphasis should be placed on two-dimensional capabilities, with a performance (drag and lift coefficient) predictor and with deice system simulations.

Considerable work had been done over the past 16 years to replace the questionable Gray correlations published in reference 3. New correlations were derived from rotorcraft airfoil icing tests in the early 1980s and presented in reference 2, but additional comparisons with test data from other tests for other airfoil models are warranted. The correlations have become the foundation for codes to calculate the effects of icing on rotorcraft and propeller performance. While aircraft-type-dependent adjustment factors may be necessary to achieve the level of agreement necessary for use of this type of code for certification, these correlations may constitute the best tool (adequate performance prediction and shedding accuracy at a reasonable cost) for the prediction of rotor performance in icing for many years to come.

One of the most important factors for flight in icing is proper training of flight crews. Simulators for aircraft control system development and pilot training are used extensively in the rotorcraft industry. However, none of these simulators have been modified to incorporate an icing module that can be used to train pilots in the proper techniques for controlling the helicopter for flight in icing and what to expect in icing conditions.

GAP ANALYSIS

The needs for the rotorcraft industry are currently focused on the optimization and certification of inlet ice protection and the design, development, optimization, and certification of main rotor, tail rotor, and proprotor ice protection systems. Since inlet ice protection requirements are similar to those for other segments of the industry, the associated gaps in the simulation methods will not be discussed here. The text below will focus on rotor simulation requirements.

Two main categories of simulation gaps exist—those associated with computer codes and those associated with test methods and techniques. At this time the existing codes that are used to predict ice accretion, both the NASA LEWICE family of codes and the empirical rotor codes [2 and 4] have reached a state of development to enable them to be used for design studies and for the calculation of rotor performance in icing. However, the validation and acceptance of these codes by system designers and certification and qualification authorities is lacking because flight data for use in correlation is very limited.

The ease of use of these tools must be improved and the general acceptance of these codes for design work must be expanded. Validation must be brought to a higher level so that the confidence levels and limitations are known and substantiated. It is necessary to also determine how good a code must be in order to be a useful code, that is, when is a code good enough to meet the requirements of the design team and certification team. Even if the tool has uncertainties, the cost-benefit relationship for use of the tool and the inherent variability in the physics of icing may make the widespread use of the tool worthwhile. Current work in the Federal Aviation Administration (FAA) Working Group (WG) 11A may be useful in identifying the kind of uncertainties that may be acceptable for rotor icing code acceptance.

Methods of simulating ice accretions and producing artificial icing conditions offer significant promise for qualifying ice protection systems and for determining flight characteristics with ice accreted on the aircraft. It is necessary to understand limitations

of methods and provide acceptance or validation of test methods. Any limitations associated with scale models must be better understood. Once limitations are understood, it should be possible to proceed to validate methods within these limitations.

There are no U.S.-made rotorcraft certified for flight in icing conditions, partly because of the high cost of certification tests. There is a need to have rotorcraft a part of the all-weather aircraft fleet, and the use of simulation methods can aid in the confirmation of the suitability for flight in icing at a reasonable cost.

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USE OF ICING SIMULATION TOOLS IN DESIGN AND CERTIFICATION

Aircraft Engines

Philip Chow, AlliedSignal

CURRENT USES OF ICING SIMULATION TOOLS

Both analytical and experimental simulation tools are used in developing a propulsion engine. For a new engine design, experience and design guidelines are normally used during the conceptual phase to identify locations or components within the engine where icing is a concern. Numerical simulation tools are used during the preliminary design phase to define the icing boundary conditions on these engine components. Icing particle trajectory computer codes are the most frequently used simulation tool at this stage. These codes are used to predict the impingement limits and the local collection efficiency of the component. After the boundary conditions are defined, analysis is performed to determine whether the engine component requires any active deice or anti-ice devices for safe engine operation. If the feature is deemed necessary, detailed design will follow.

After the detailed design of the anti-ice or deice feature is completed, a component level validation test is generally conducted. The icing conditions identified during the preliminary design of the component should be simulated in this test. Altitude pressure environment is generally not simulated. Either a full development engine or a test rig may be used for the test. A full development engine test would produce a true simulation of the engine environment. On the other hand, a test rig provides more flexibility by allowing independent changes of design variables. A test rig also makes it easier to set up video devices to record the ice accretion on those engine components located within the engine core. An example of an icing rig test is the testing of a fan spinner alone in an icing tunnel to investigate the ice accretion characteristics and anti-ice heat requirement.

Safe operation of the engine in an icing condition will be demonstrated during the certification phase of the program. The icing test generally conducted during this phase is a pass/fail test designed to show that the engine meets all the specifications and regulations defined by the customer and the certification agencies. The 14 Code of Federal Regulations Part 33.68 requires that the engine demonstrate satisfactory operation in environmental icing conditions within the icing envelope cited in Appendix C of 14 CFR Part 25. This icing envelope defines the altitude boundaries from sea level to 30,000 feet and an ambient temperature from -40° to 32°F.

The Federal Aviation Administration (FAA) has also issued an Advisory Circular, AC 20.73, which permits equivalent sea level testing (paragraph 33.b "Acceptable means of compliance"), if it is combined with a critical operating point analysis of the certifying engine. As a result, an engine manufacturer may choose to demonstrate compliance to the regulation by either an icing test with altitude effects simulated or an equivalent sea level icing test at the specific points depicted in AC 20.73.

Three test techniques are available to conduct an engine icing test with altitude effects. The first one is a natural icing flight test. The second is an altitude flight test in a

simulated icing environment created by an icing tanker. The third is the simulation of both altitude and icing conditions in a ground facility.

The natural flight test approach does not need any simulation. However, to find the severe icing conditions depicted in the 14 CFR Part 25, Appendix C envelope is difficult under the cost and schedule requirements of a test program. Therefore, most natural icing flight tests are conducted at a lower liquid water content than the Appendix C level. Analysis is conducted to extrapolate the test results to the Appendix C level using a correlated icing model.

The second option is an altitude flight test with a simulated icing environment. In this case, a flying water tanker is used to generate the 14 CFR Part 25, Appendix C icing conditions. The test aircraft then flies in formation behind the tanker with the test engine engulfed in the simulated icing cloud. The concern on this type of testing is primarily flight safety and the uniformity of the icing cloud at the test engine inlet. This method has been employed by engine certification programs, but it is seldom used in recent certification trials due to concern about icing cloud uniformity.

The third method using a ground facility engine test is the most popular method due to the ability to control the environmental conditions and its relative safety. However, most engine manufacturers choose to certify their engines by using the AC 20.73 equivalent test points to test at these icing facilities. Altitude test facilities are used in cases where simulation of altitude effects, rather than use of equivalent test points, is deemed important for the certification program.

LIMITATIONS AND NEEDED IMPROVEMENTS OF ICING SIMULATION TOOLS

Improvements on preliminary design and detailed design analytical icing simulation tools can benefit all the aerospace engine manufacturers. During the preliminary design phase, a sophisticated icing simulation code with axisymmetric ice particle trajectory prediction is required to define boundary conditions and perform trade-off studies. Therefore, an important characteristic of this code is the ability to input and change component geometry easily. Currently this computer code is not available in the public domain.

In-house icing codes are commonly used to perform this function. Due to the proprietary nature of the in-house codes, the technical development of these codes is not coordinated throughout the industry. A common axisymmetric icing code, supported by a national research organization, would ease the burden for all engine manufacturers in keeping up with the latest icing technology developments. The synergy of effort would reduce the cost of engine development and improve the competitiveness of all engine manufacturers.

Three-dimensional (3D) computer simulation codes are currently used to fulfill design analysis needs for more sophisticated geometry encountered during the detailed design phase of an engine program. A common characteristic of the current 3D icing code is the combination of aerodynamic flow field calculation and ice trajectory calculation within the program. The coupling of aerodynamic flow solution and ice accretion solution is a necessary feature in predicting accurate ice shape. However, this feature is not important for an engine component that is anti-iced and is expected to maintain ice-free surfaces in all environmental conditions. The flow field around the engine component is often

analyzed independently in the design process for aerodynamic efficiency evaluation. Repeating the same calculation and modeling steps in the icing analysis would be wasteful. A 3D ice trajectory code that can accept an aerodynamic flow field solution from any commonly used flow solver would bridge this gap. The benefit of this improvement is that it reduces the cycle time of an icing analysis. This will encourage more sophisticated icing analysis to be conducted and improve the overall safety of the engine.

As discussed in the simulation requirement section, a test rig would be a preferred vehicle for conducting component validation testing during the development phase of an engine program. Simulating the engine conditions in a test rig would allow better viewing of the ice accretion process. Unfortunately, a good icing simulation rig for an engine component does not exist today.

The most important technology gap in developing this rig is the ability to simulate the discontinuity between icing particle temperature and the local air temperature at the component location. The icing wind tunnel uses subfreezing air flow to cool down and maintain the liquid water droplets at supercooled temperatures after they leave the spray nozzles. A subfreezing tunnel temperature is therefore a necessary condition in the icing simulation. For an actual engine operating in an icing environment, a supercooled liquid droplet entering the engine will experience a continuously increasing air temperature environment as it passes through the compressor stages. On the other hand, the droplet's own thermal mass prevents its temperature from increasing at the same rate as the air temperature. The result is a mismatch between the local air temperature and the icing particle temperature on any component surface downstream of the first compressor stage of the engine. Since both air and droplet temperatures are important parameters in the heat balance that determines the ice accretion rate and the ice shape characteristics, the inability to simulate the temperature mismatch is a significant gap in providing an accurate icing rig for engine component development. If this technology gap is bridged, a meaningful icing rig for engine components can be built. Engine manufacturers will benefit by having a tool that can produce data to calibrate their icing design tools and methodologies. This will lead to a safer and a more competitive engine design.

A full engine icing test is generally required during the certification phase of a new engine development program. One of the techniques that simulates altitude effect is to conduct a flight test behind a simulated icing cloud generated by the flying tanker. One attribute of this approach is that the cloud generated by the spray bar may have a higher water concentration distribution at the center of the cloud than in the outer region. If the test engine centerline is aligned with the cloud centerline, the spinner and inner hub region of the fan will be exposed to higher liquid water content than the desired certification level. Since icing on the spinner and the fan hub are often the root causes of icing problems in an engine, accurate simulation of liquid water content at these locations is necessary for a meaningful icing test. Improvements to the uniformity of simulated icing clouds generated by flying tankers can significantly increase the value of this tool to engine manufacturers.

USE OF ICING SIMULATION TOOLS IN DESIGN AND CERTIFICATION

Ice Protection Systems

Kamel Al-Khalil, Cox and Co.

This paper will specifically address issues related to practical usage of simulation tools by ice protection system manufacturers. In general, ice protection system manufacturers are also designers of the system. Coverage and extent of the ice protection regions on specified aircraft components are normally discussed with the airframe manufacturer, and an agreement is reached based upon discussion of the analysis and experimental results presented by the ice protection manufacturer. The following discussions will be limited to usage of simulation tools as other topics are discussed elsewhere in this paper.

ICE PROTECTION SYSTEMS

Thermal systems consist of either hot gas (compressor bleed air) or electrothermal heaters. Bleed air is usually used in a fully evaporative anti-icing system that may operate as a "running-wet" system in extreme or intermittent maximum conditions. Electrothermal systems consist of anti-icing (evaporative and running-wet) and deicing systems.

Mechanical systems consist of pneumatic or electromechanical systems. These systems are used as deicers such that ice accretes on the surface and is periodically removed by displacing the aircraft skin or "boot" underlying the accumulated ice and breaking the ice bond.

Freezing point depressant systems consist of an anti-icing fluid that is pumped through small orifices on the leading edge and mixed with the impinging supercooled water. The result is a liquid mixture that has a freezing temperature below pure water freezing point and that runs back over the surface.

The choice of a particular system depends on several factors that are beyond the scope of this discussion.

ANALYSIS AND DESIGN

The first step in the design process is to define the geometry and the operating envelope of the aircraft. Following is the analysis and prediction of ice impingement zones and rates (collection efficiency). Once direct impingement zones have been determined, a preliminary method of ice protection is selected and analyzed for performance and feasibility. Other issues like frozen runback and its effect on aerodynamic performance as well as foreign object damage (FOD) possibilities are also addressed.

USE OF SIMULATION TOOLS

The ice impingement zones are determined using a combination of tools. Analytical tools are used to give a first-cut prediction. The National Aeronautics and Space Administration (NASA) LEWICE ice accretion code is used extensively for that purpose. The two-dimensional (2D) version is a well documented and robust tool. Its application

to three-dimensional (3D) geometries such as swept and/or tapered wings is possible with applicable methods and corrections. A more accurate prediction on complex geometries and flows is obtained using 3D flow field and trajectory simulation codes such as LEWICE 3D. The user must have some experience using this code and know its limitations. For example, confidence level in the results is higher in the case of lifting surfaces (airfoils) than in the case of flows around and inside curved ducts (i.e., engine inlets). Additionally, prior experience and similarity to earlier ice protection products are essential to correctly interpret computational analysis. Furthermore, photographs of ice shapes and surface coverage during flight can be very helpful in the design of a system.

In addition to the impingement limits, the accretion rate is also predicted by LEWICE. The results are then used in other in-house developed thermal calculation codes as well as the more detailed NASA ANTICE computer code to predict the total and local power distribution required to protect the aircraft surface against ice accumulation. Several private companies own a proprietary code with similar capabilities. In case a thermal deicer is used, a code such as LEWICE/THERMAL can be used to simulate the transient process of heating, ice shedding, and cooling during the deicing cycle.

The next step is usually designing and fabricating a prototype model for testing, usually in an indoor icing wind tunnel. In the case of a thermal anti-icing system, for example, several zones are designed with individual heaters, where each zone is controlled separately. A data acquisition system and a flexible control system are required to operate the test setup at the various operating conditions. The heaters can be operated to control a certain temperature (e.g., heater or surface) or can be operated in constant duty cycle for a fixed power per heater.

One of the most valuable tools for ice protection system manufacturers is an icing wind tunnel. Depending on availability and cost of rental/operation, several entries may be required to refine a specific design. Additionally, in the case of ice protection system manufacturers who operate their own icing facilities, more emphasis and development time may be placed on icing tunnel results than on computer simulation codes. This is especially true when the flow in and around the component to be protected is complex and highly three-dimensional in nature. An example is the flow through a turboprop engine inlet that normally includes a by-pass/bird catcher and is located in the wake of the propeller stream. In these cases, because of uncertainty as to the validity of computer predictions and also the extended time required to set up and analyze the problem, it is generally not warranted to carry out extensive computational studies.

Specific designs require special attention to particular issues. For example, in thermal anti-icing and deicing systems, runback refreeze issues are addressed. The amount, shape, and location may or may not have a significant effect on the aircraft aerodynamic performance. Also, the possibility of runback ice shedding and impacting essential downstream components is addressed. On the other hand, mechanical deicing systems require special attention to deicing cycle time issues. Generally, each particular application or system requires attention to several specific issues that are beyond the scope of this document.

Following the computer analysis and icing tunnel tests, results are analyzed and a final design configuration is selected. If the airframe manufacturer or the Federal Aviation

Administration (FAA) requires a tunnel demonstration of the final design, a prototype is fabricated for that specific purpose. Otherwise, production units of the ice protected components are produced for the certification process in natural icing conditions. System development rarely depends on flight testing in natural conditions due to the high cost involved and the uncontrolled nature and inherent variability of atmospheric icing conditions, which make parametric analysis almost impossible to conduct. Moreover, the liquid water content (LWC) encountered during flight is usually lower than tested in tunnels. When encountered in-flight, high LWC conditions (within the 14 CFR Part 25 envelope) are not usually sustained long enough to consider a steady state had been reached for the ice protection system performance.

CONCLUDING REMARKS

Current computer simulation codes are very useful tools but have some limitations. They are frequently relied upon for preliminary designs to the point that 2D simulation codes are often applied locally to 3D geometries as in the case of moderately swept wings. An icing tunnel facility is an indispensable tool for the development and validation of ice protection system performance. The experience gained over the years, combined with the use of analytical tools and icing tunnel facilities, usually leads to ice protection systems that perform adequately in natural icing conditions. However, pilots must observe system limitations particularly in conditions that exceed the icing certification envelope.

CAPABILITIES AND LIMITATIONS OF ICING SIMULATORS IN THE SIMULATION OF ICING CONDITIONS FOR THE DESIGN AND CERTIFICATION OF AIRCRAFT AND ENGINES

Tunnels

David Anderson, Streathill

CURRENT SIMULATION CAPABILITIES

Icing wind tunnels provide controlled and repeatable simulations of in-flight icing encounters for a variety of evaluations and studies. Icing tunnels are generally based on aerodynamic wind tunnel designs with two additional features: (1) a refrigeration system and heat exchanger to cool the air to controlled temperatures below freezing and (2) a system for spraying water into the airstream with control of both drop size and water flow to simulate an icing cloud. Test conditions produced in icing wind tunnels can be broadly categorized as the simulation of 14 Code of Federal Regulations (CFR) Parts 25 and 29, Appendix C-defined environments or the simulation of outside-of-the-envelope, or exceedence conditions, e.g., supercooled large droplets (SLD). The Appendix C-defined environments are defined in terms of temperature, liquid water content (LWC), and median volume diameter (MVD) averaged over specific distances in natural atmospheric environments. The types of tests performed in icing wind tunnels vary widely but will generally fall under the following categories:

- Airfoil/airframe
- Ice-protection system
- Icing physics
- Ice-accretion code validation
- Propulsion system
- Icing instrumentation and aircraft sensors (pitot probes, total temperature probes, etc.)

The icing tunnel information which follows was obtained from published literature, supplemented by discussions with personnel from various facilities. The information is intended to apply as much as possible to all icing tunnels. However, differences between tunnels make it necessary from time to time to discuss issues and capabilities with reference to individual tunnels. Because the NASA Glenn Icing Research Tunnel (IRT) is the oldest and largest of the U.S. icing tunnels, it has been the subject of numerous studies detailing tunnel performance characteristics and has been used extensively for icing research. Consequently, there is considerably more published literature dealing with this tunnel than with others, and much of the data used in this paper come from these IRT studies. When the characteristics presented are specific to the IRT, however, this will be indicated.

Icing wind tunnels provide a controlled, repeatable and safe environment for the simulation of much of the in-flight icing regime.

The strengths of icing wind tunnels are as follows:

- Repeatable test conditions
- Controllable test conditions
- Ready simulation of much of 14 CFR Parts 25 and 29, Appendix C envelope

- Low operating costs relative to flight testing
- Low relative model costs (due primarily to model size and scale)
- Safe and comfortable testing environment
- Rapid and economical parametric evaluations
- Accessibility for observation, recording, and examination of ice accretions and icing processes
- Year-round availability (for most tunnels)
- Readily available to investigate exceedance conditions, e.g., SLD
- Experience base—Over 50 years of wind tunnel test operations experience

The general capabilities of the icing tunnels in the U.S. are summarized in table 1. Recently the Society of Automotive Engineers (SAE) AC-9C Committee surveyed icing facilities around the world. Additional information on icing tunnels as well as other ground testing facilities in the U.S., Canada, and Europe are included in the AC-9C Committee report [1]. A more detailed discussion of icing tunnel capabilities will be given in the section entitled "Range of Capabilities."

TABLE 1. SUMMARY OF U.S. ICING WIND TUNNEL CAPABILITIES

Organization	Tunnel Location	Tunnel Name	Test Section Size	Max Airspeed (mph)	Temp Range (°F)	MVD Range (µm)	LWC Range (g/m³)	Notes
AEDC	Tullahoma TN	R-1D	3-ft diam	600	-20 – 100	15 – 40	0.2 – 3.9	4
BFGoodrich	Uniontown OH	Icing Wind Tunnel	22 x 44 in	200	-22 – 32	10 – 50	0.4 – 3	2
Boeing	Seattle WA	Boeing Research Aerodynamic Icing Tunnel	5 x 8 ft	170	-25 – 60	15 – 40	0.5 – 3	1
Boeing	Seattle WA	Boeing Research Aerodynamic Icing Tunnel	4 x 6 ft	290	-25 – 60	15 – 40	0.5 – 3	1
Boeing	Seattle WA	Boeing Research Aerodynamic Icing Tunnel	3 x 5 ft	400	-25 – 60	15 – 40	0.5 – 3	1
Cox & Co.	New York NY	LeClerc Icing Research Laboratory	28 x 46 in	220	-22 – 32	15 – 50	0.25 – 3	2, 3
Cox & Co.	New York NY	LeClerc Icing Research Laboratory	48 x 48 in	120	-22 – 32	15 – 50	0.25 – 3	2, 3
FluiDyne	Minneapolis MN	22 x 22 Icing Wind Tunnel	22 x 22 in	610	amb	10 – 35	0.1 – 5	
NASA Glenn Research Center	Cleveland OH	Icing Research Tunnel	6 x 9 ft	400	-22 – 33	14 – 50	0.2 – 5	1, 2, 3
Rosemount	Burnsville MN	Icing Wind Tunnel	10-in diam	210	-22 – 86	15 – 40	0.1 – 3	

Notes:
(1) Rapid Spray Start, (2) Cold Room, (3) Scavenge System for Engine Inlet Tests, (4) Altitude Simulation Capability

All tunnels except the FluiDyne use refrigeration systems to control air temperature. The FluiDyne tunnel depends on outside ambient air.

State of the Art for Icing Tunnels

Icing wind tunnels are designed and operated to simulate much of the icing environment as defined in the 14 CFR Parts 25 and 29, Appendix C. This objective is achieved with spray bar arrays using multiple air-atomizing nozzles which permit somewhat independent control of cloud liquid water content and droplet size. Characteristics of typical spray systems along with improvements recently adopted by some tunnels will be described in this section. A brief discussion of other significant features of icing tunnels will also be given.

Water spray systems may require a minute or more to stabilize once the water valves are opened. Figure 1(a), taken from a test in the NASA Glenn IRT in 1995, shows how cloud MVD and LWC, determined from measured spray bar air and water pressures responded after spray initiation. For ice accretion tests requiring sprays on the order of 10 min or more, the stabilization period will normally not affect the final ice shape; however, it is desirable to increase the duration of the spray to account for the lower-than-required LWC during the start-up transient. For short-duration tests where the quantity and shape of ice are important, it is especially important to add a suitable correction to the desired spray time. The amount of the additional time will be dependent on the facility cloud response characteristics. One way to avoid the start-up transient is to use a retractable shield in front of the model to protect it from ice accretion until the spray has stabilized.

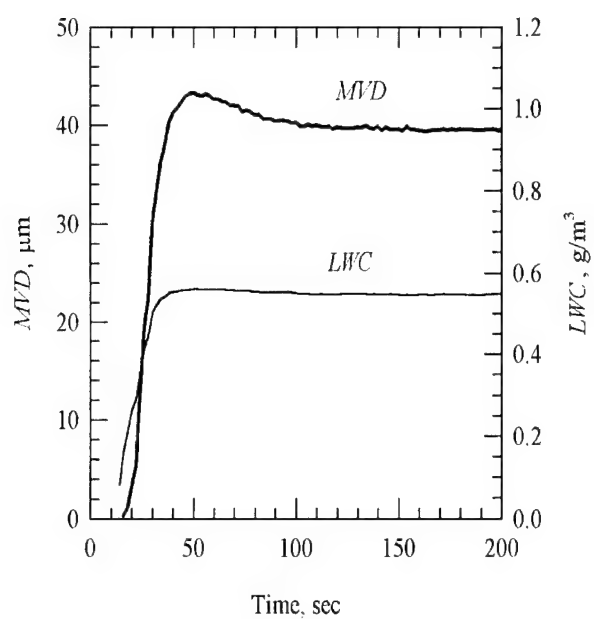


FIGURE 1(a). TYPICAL RESPONSE OF IRT CLOUD CONDITIONS AFTER SPRAY INITIATION, OCTOBER 1995 TEST WITHOUT RAPID-START SPRAY SYSTEM

A significant improvement in spray initiation was recently introduced by the Boeing Research Aerodynamic Icing Tunnel (BRAIT) [2]. In that tunnel, solenoid valves control water flow for each nozzle. Desired air and water pressures are established prior to starting the spray, with water recirculated until the solenoid valves are opened. When the IRT spray system was rebuilt in 1997, this rapid-start feature was incorporated [3]. Figure 1(b) shows the MVD and LWC response for a typical test in the IRT using the current spray system. With this system, even very short duration sprays can be made without start-up transient effects and without the need for a retractable shield to protect the model.

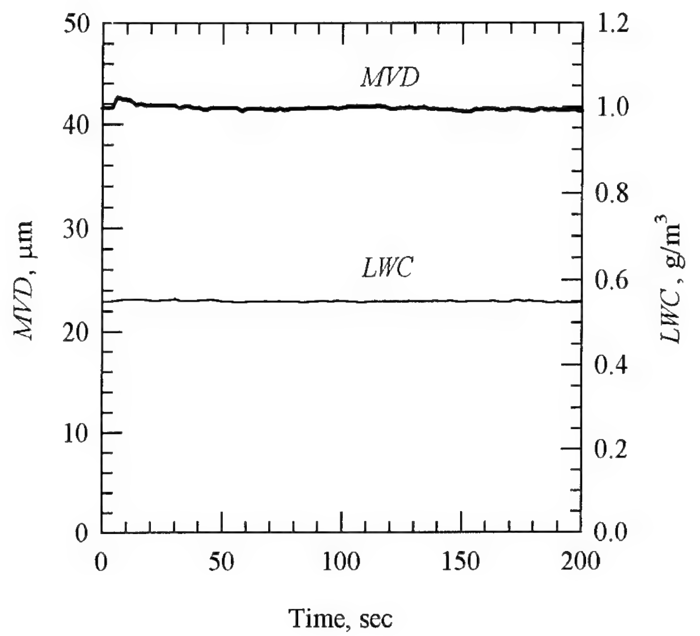


FIGURE 1(b). TYPICAL RESPONSE OF IRT CLOUD CONDITIONS AFTER SPRAY INITIATION (March 1998 test using rapid start spray system)

The upgrades to the IRT spray system made in 1997 also included the potential capability to make a step change in LWC during an icing spray. Two water manifolds are used in each spray bar, and the water pressure in each manifold can be controlled individually. The ability to turn off the spray from one manifold and turn on the other while spraying has not yet been fully tested. However, small changes in LWC can be realized during a spray using a single manifold because of the spray bar system's rapid response to changes in pressures. Limited tests of this capability have been successful. The dual manifold arrangement also permits the simultaneous installation of two nozzle sets with different flow ranges. Each set would be fed by a separate manifold. With both nozzle sets in place, either can be selected for a given spray without labor-intensive nozzle changes.

Another major component of an icing tunnel is the heat exchanger, which cools the airflow to the desired temperature. The emphasis in the design of early heat exchangers was to obtain maximum surface exposure to the airflow. These designs included panels at an angle to the airflow that introduced flow distortions into the air stream. The recent state-of-the-art designs, incorporated into the BFGoodrich, Boeing, Cox, and NASA

Glenn icing tunnels, use flat heat exchangers for minimum airflow distortion. Automatic control systems maintain fan speeds, cloud conditions, and tunnel temperatures within narrow limits for the duration of a simulated icing encounter.

Icing tunnels include a number of additional features that enhance their testing capability. Observation windows are provided for users to view, photograph, or videotape the model as ice is accreting. Several tunnels have cold rooms near the test section to permit ice shapes produced in the test section to be examined and measured off-line. Cold rooms can also be used to perform experiments for which airflow is not required. Some icing tunnels also furnish a scavenge system to provide airflow through engine inlet models. With these systems, internal flow through the model is ducted to an altitude exhaust facility with control valves and metering devices so that the internal flow rates can be varied. This feature is required to simulate the airflow in and around engine nacelles to obtain correct droplet trajectories when testing inlets. In addition to the above capabilities, icing wind tunnels typically provide users with instrumentation to measure and record model angle of attack and tunnel conditions as well as model temperature and pressures. Electrical power and pressurized air supplies permit testing of deicing and anti-icing systems. The IRT also has available laser sheet flow visualization, various kinds of video (including high speed and close-up) and still photographic services, and a scanner located in the cold room to record three-dimensional coordinates of ice shapes.

Range of Capabilities

Table 1 shows the capabilities of several icing tunnels in use in the U.S. Test sections range in size from 10-in diameter to 6 by 9 ft. Most tunnels are capable of operating with airspeeds as low as 50 mph with maximum speeds of 200-300 mph. The IRT, BRAIT with 3- by 5-ft test section, and FluiDyne tunnels can operate at higher maximum speeds. Numbers quoted in table 1 are generally for empty test sections, so practical airspeed is dependent on test-section blockage and drag coefficient for the test assembly. For example, in the IRT the maximum speed has been estimated to drop from 430 mph in an empty test section to 350 mph when a model assembly with 5 percent blockage and drag coefficient of 1.7 is installed [4]. The FluiDyne tunnel uses cold ambient air for the low temperature air supply; thus, tests can only be run during the winter. The other tunnels use refrigerated air to establish the test-section temperature and are capable of year-round operation. Most tunnels can control temperatures to as low as -25°F, and possibly lower, depending on airspeed. Only the AEDC R-1D provides control of the test-section pressure to simulate altitude. The other icing facilities in table 1 are effectively sea-level tunnels.

The calibrated range for MVD is typically between 10 and 50 μm because, to date, that has been the range of interest for nearly all icing studies. The LWC range depends both on airspeed and on nozzle air and water pressures. The airspeed dependency exists because the LWC for an icing tunnel cloud is simply the mass flow rate of water from the nozzles divided by the volume flow rate of air in the tunnel loop. The calibrated range may extend from a few tenths of a g/m^3 at the highest tunnel speeds to 5 g/m^3 or more at the lowest tunnel speed.

The LWC range depends to some extent on the MVD. As an example, figure 2 shows the calibrated range of LWC vs MVD for the IRT superimposed on the 14 CFR Part 25,

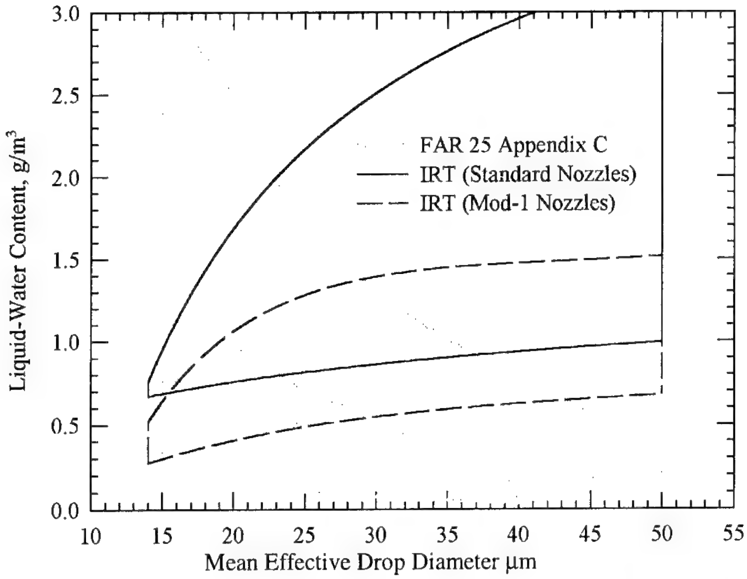


FIGURE 2(a). CLOUD PRODUCED BY IRT NOZZLES COMPARED WITH 14 CFR PART 25, APPENDIX C ENVELOPE OF NATURAL ICING CONDITIONS—AIRSPEED 150 mph

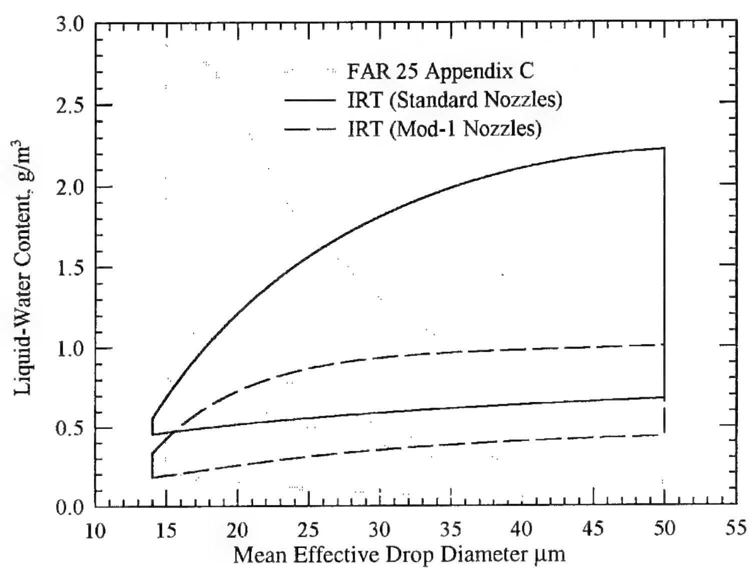


FIGURE 2(b). CLOUD PRODUCED BY IRT NOZZLES COMPARED WITH 14 CFR PART 25, APPENDIX C ENVELOPE OF NATURAL ICING CONDITIONS—AIRSPEED 250 mph

Appendix C envelope. The Appendix C continuous maximum conditions are indicated by the lower gray outline, and the intermittent maximum conditions by the upper gray outline. Figure 2(a) is for a test-section airspeed of 150 mph and 2(b) is for a speed of 250 mph. For this tunnel, at 150 mph for a 20-µm-MVD cloud, the LWC can be varied

from 0.4 g/m^3 (with Mod-1 nozzles) to 1.7 g/m^3 (using standard nozzles). At 250 mph, the LWC range is from 0.25 to 1.2 g/m^3 for an MVD of 20 μm. At the same speed, but with an MVD of 50 μm, the range of LWC is 0.45 to 2.2 g/m^3. It is evident from figure 2 that a significant portion of the Appendix C envelope is covered by the icing tunnel spray.

When tests are required at 14 CFR Part 25, Appendix-C conditions outside the tunnel envelope, test-condition scaling methods can often be applied. Suppose, for example, that a test is needed to determine the ice shape which would result from a 4-min exposure of a certain model to a static temperature of 17°F, an airspeed of 250 mph, droplets with an MVD of 30 μm, and an LWC of 0.25 g/m^3. Figure 2(b) shows that, for the IRT, the desired MVD and LWC cannot be obtained simultaneously at this speed. Scaling methods are systems of equations that allow a user to calculate new test conditions to produce the same nondimensional ice shape. The scaling equations are derived from the physics of ice accretion such that the scaled test satisfies similarity in model geometry, flow field, droplet trajectory, water catch (ice accumulation), and heat balance.

For the situation in which the tunnel LWC needs to be scaled while using a full-scale model, there are several methods available. All of these are approximate, because there are more similarity parameters that could be used than there are test conditions that need to be determined. Probably the oldest and simplest scaling method satisfies the equation LWC × time = constant. This expression is derived by equating scale water catch to the reference (desired or full-scale) value while keeping model size, temperature, airspeed, and droplet size at their reference values. For the example above, this method would suggest that simply increasing the LWC from 0.25 to 0.35 g/m^3 and decreasing the time from 4 to 2.9 min should give the same ice shape. This method is easy to apply and is effective for very small changes in LWC or for rime conditions, but has been shown to distort the ice shape, in general, for glaze conditions [5 and 6].

Another method of scaling LWC is the Olsen method. In this method, model size, airspeed, droplet size, and water catch are again maintained at the reference values, and in addition, the freezing fraction (one of the parameters derived from the heat balance) is matched [5 and 6]. With the scale LWC chosen by the user, this method results in scale temperatures as well as spray times that are different from the reference. The Olsen method appears to be more effective for scaling glaze ice conditions than LWC × time = constant, but it has not been evaluated for LWC scaled by more than approximately ±30 percent (LWC scaled up from 1 to 1.4 g/m^3 and down from 1 to 0.8 g/m^3).

Finally, the Ruff method [7] requires one more similarity parameter to be matched. With model size unchanged from the reference and scale LWC chosen, it maintains water catch, water-droplet collection efficiency, the freezing fraction and a water-energy-transfer parameter at the respective reference values. The resulting equations can be solved to determine the scale spray time, MVD, airspeed, and temperature. Because more similarity parameters are satisfied with this method, it can be expected to provide better scaling than the Olsen method, but has had only limited testing. In these tests, LWCs of 0.8 and of 1.2 g/m^3 produced matching shapes [7].

In principle, these same methods should also be applicable to scale either droplet size or airspeed. The Olsen method has not been tested for this application. The use of the Ruff

method to scale LWC from 0.8 to 1.2 g/m^3 required changing speed from 214 to 136 mph and drop size from 15.4 to 20 μm. Thus, the test was equally valid to demonstrate scaling for either of these test parameters as well as LWC. Additional evaluations of both the Olsen and Ruff methods for scaling test conditions are needed because they are potentially valuable tools to simulate conditions outside the operating range of icing tunnels. The Ruff method can also be used to scale model size, and a discussion of model size scaling is given in the section entitled "Scaling to Extend Effective Tunnel Capability."

MVDs higher than 50 μm could be obtained with existing nozzles if there were a need sufficient to warrant the additional calibration work required. The IRT, for example, has been calibrated for five specific SLD conditions. This calibration covered a range of MVD from 70 to 270 μm at one LWC value for each drop size and for three airspeeds. More extensive large-droplet calibration has been carried out at the BRAIT. However, until there are specific certification requirements for large-drop conditions or specific customer requirements for testing, there is no reason to do additional calibration. Further discussion of SLD issues can be found in the sections entitled "Cloud Calibration, Uniformity and Calibration Accuracy" and "For Conditions Outside 14 CFR Part 25, Appendix C."

A limited amount of work has been done to demonstrate that mixed-phase (water particles coexisting in liquid and solid states) conditions can be simulated in icing tunnels. One approach is to control spray-bar air and water temperatures using existing tunnel spray systems [8]. Work at the Arnold Engineering Development Center (AEDC) using two sets of nozzles, one to produce water and one to produce solid particles, has been reported by Riley [9]. Riley reviews other approaches to produce and entrain ice and snow into a tunnel airstream, as well. Injection of ice particles produced external to the tunnel might be used to induce crystallization of supercooled droplets or supply the solid particle density needed. External-generation methods present major difficulties in producing sufficient quantities of particles and then injecting and distributing the particles uniformly in the cloud. Additional studies of mixed-phase conditions and methods to simulate them in icing tunnels are needed.

Cloud Calibration, Uniformity, and Calibration Accuracy

Icing tunnels are calibrated to define airflow and icing cloud quality. Although there is no universal standard for calibrating the icing tunnel cloud, several tunnels have adopted the same procedures for establishing a uniform icing cloud as well as for measuring LWC. The procedures used in the IRT have been described by Ide [10, 4]. The same methods are also used in the Boeing BRAIT and the Cox LeClerc Icing Research Laboratory [11].

The uniformity of LWC is assessed by accreting ice on vertical and horizontal 2-in. diameter pipes placed at multiple positions in the tunnel test section. Grids of rectangular bars have also been used in place of the vertical and horizontal pipes. The girth of the iced pipes or the thickness of ice accreted on the bars is measured at evenly spaced locations. All measurements are then normalized to the measurement at the center of the tunnel to give relative values.

The flow entering the test section of an icing tunnel is distorted somewhat by tunnel features, such as the spray bars and structures supporting them. Thus, to obtain a uniform cloud in the test section, nozzles must be spaced nonuniformly in the spray bars. In order to determine where the spray from different nozzle locations ends up when it reaches the test section, a series of runs are made using two widely spaced spray bars at a time. The peak ice thicknesses on the vertical pipes or on the grid is then recorded. The test is repeated using vertical lines of nozzles at different horizontal locations and accreting ice on the grid or on horizontal bars. The information gained from these tests makes the movement and addition of nozzles to the spray system more systematic. However, the process of establishing a uniform cloud still involves considerable trial and error and is therefore very time consuming. A cloud is usually considered to be of acceptable uniformity when the LWC varies by no more than ±20 percent from the value at the center of the test section. The size of this uniform cloud will always be smaller than the physical height and width of the test section, because the cloud LWC decreases near the walls. In the IRT, the size of the uniform cloud is approximately 5 ft high by 5 ft wide at 200 mph [3], and in the BRAIT, it is roughly 3.5 ft wide by 3.5 ft high at 150 mph [2]. The uniform cloud size tends to shrink as speed increases; for example the BRAIT cloud is about 3 ft by 3 ft with several small pockets of LWC outside the ±20 percent range at 270 mph [2]. The IRT cloud uniformity has been evaluated only up to a maximum speed of 300 kt.

For the 14 CFR Part 25, Appendix C conditions, a standard icing blade [12] is used to measure the LWC in the center of the IRT test section. The blade is made of aluminum and is 6 in. long 3/4 inch deep, and 1/8 in thick. The tunnel is usually chilled to 0°F for these tests to provide rime ice. For tunnels without rapid-start spray systems, it may be necessary to shield the blade while spray conditions stabilize; the shield is no longer necessary in the IRT. The exposure time is adjusted to allow between 1/16 and 3/16 of an inch of ice to form on the 1/8 in-wide leading edge of the blade. The thickness of ice on the blade is measured using a chilled micrometer. The ice thickness, the exposure time, and the free stream velocity are then used to calculate LWC, knowing the collection efficiency of the blade and the ice density. The collection efficiency of the blade can be determined from two-dimensional particle trajectory codes. The accepted average value of ice density for rime is 0.88 g/m^3.

Droplet size and distribution are determined with laser-based probes, including the Forward Scattering Spectrometer Probe (FSSP), the Optical Array Probe (OAP), and the Phase Doppler Particle Analyzer (PDPA). The first two are manufactured by Particle Measuring Systems (PMS) and the PDPA is manufactured by Aerometrics. The two PMS probes were developed for use on aircraft to measure cloud characteristics in flight and they can be inserted into the icing tunnel test section. The PDPA is used nonintrusively to view the cloud through observation windows.

The two PMS probes are used together to obtain a complete distribution of drop sizes. The FSSP measures droplets with diameters at the smaller end of the spectrum. In this instrument, a laser is used to illuminate single particles as they traverse the sample volume. The forward-scattered light is focused onto a photodiode to measure the intensity, which increases with particle size. The OAP is used to measure droplets with larger diameters. In this instrument, a collimated laser beam is used to illuminate

particles. As a particle passes through the beam, its shadow is projected onto a linear photodiode array. The number of diodes shadowed determines into which size bin the particle will be placed. The instruments used in the calibration of the IRT have a range of 2 to 47 μm for the FSSP and 15 to 450 μm for the OAP. The data from the two instruments are combined into a single droplet distribution by taking into account the sample area, measurement time, and bin widths of each instrument. Because the ranges of the two instruments overlap and the first two bins of the OAP characteristically undercount, these bins of the OAP data are discarded.

The PDPA measures droplet sizes over the whole range of size distributions of interest for typical icing clouds [13]. Thus, a complete distribution is obtained with a single instrument. It uses a laser system similar to a Laser Doppler Velocimeter, in which the droplets pass through intersecting beams to produce a far-field interference fringe pattern. It records both droplet size and velocity.

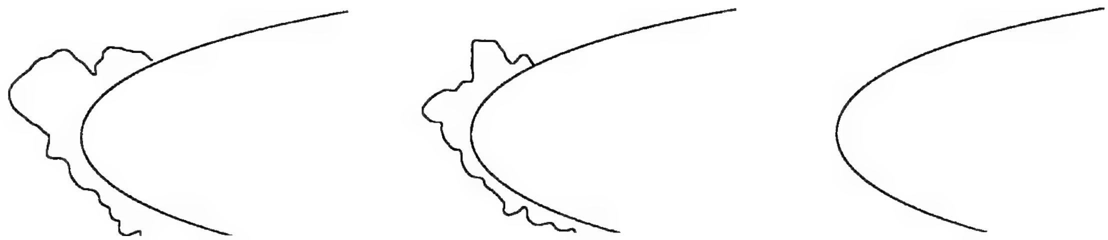
There do not appear to be any published studies which have compared the drop-size distribution resulting from the spray nozzles used in icing tunnels with that seen in natural atmospheric conditions. However, an unpublished study of the IRT nozzles by Olsen in the early to mid 1980s showed good agreement of the drop-size distributions with one observed natural distribution. In nature, there are a variety of drop-size distribution characteristics all of which may produce the same MVD. In the icing tunnel, the distribution is invariant for a given LWC and MVD. It is not known how much, if at all, accreted ice shapes might be affected by variations in the drop-size distribution for a given MVD.

Another issue of importance in simulating nature is whether water droplets are supercooled. In natural icing clouds, many of the water droplets remain in the liquid state although their temperature is below freezing. In the icing tunnel, the use of air-atomizing nozzles to inject water involves a rapid expansion of the atomizing air. To prevent freezing of the water during this injection process, air and water in the spray bars are heated. The concern, then, is whether the heated water droplets are able to cool sufficiently to reach the ambient temperature by the time they enter the test section. In addition to the cooling which occurs on injection, the droplets cool further by convection as they are entrained in the airflow and carried to the test section. A code developed by AEDC [14] has been used for icing tunnels to predict water droplet cooling. It indicates that water droplets in the 10 to 50 μm range equilibrate to the air temperature by the time they enter the test section. There have not been any published experimental studies to date to directly confirm the code results for 14 CFR Part 25, Appendix C-size droplets, but research with large droplets which demonstrated that droplets are supercooled will be discussed in the next paragraph. Other work that looked at the effect of spray-bar air and water temperatures [15] have shown that ice shape with a 15-μm MVD is independent of spray-bar temperatures when the temperatures are reduced from 180° to 143°F. At 100°F, water droplets began to freeze before reaching the model, and the accretion became significantly smaller. Because ice shapes from a supercooled cloud should be quite different from the shapes resulting from a partially or fully nonsupercooled cloud, these results would suggest that even at 180°F, water droplets reach the static air temperature by the time they enter the test section.

Recent interest in conditions with droplet sizes larger than those in the 14 CFR Part 25, Appendix C envelope has led to some calibration work in both the IRT and BRAIT for these conditions. Whether these large droplets are supercooled has been questioned, because atomizing air pressure is much lower than for 14 CFR Part 25, Appendix C droplets, and there is therefore less initial cooling. Furthermore, the volume of the droplet would tend to require longer residence times to reach the ambient temperature. However, a recent study in the IRT by Miller, et al. [16] reported that the AEDC code predicted that droplets up to at least 160 μm in diameter reach a temperature within 2°F of the air temperature. Miller placed thermocouples on the leading edge of his airfoil, and these showed dramatic cooling of the leading edge at the time the cloud reached the model. This cooling was cited as evidence that the cloud droplets were at a temperature between the static and total air temperatures. Because the BRAIT residence times are similar to those in the IRT, the IRT results would suggest that large droplets in the BRAIT should also be supercooled. Whether smaller facilities like the Cox or BFGoodrich icing tunnel would also achieve supercooling of large droplets in the test section has not yet been established. However, note that the Cox tunnel has a second test section downstream of the first, and residence times to that test section should be roughly the same as the IRT. Other limitations of icing tunnels with regard to SLD operation are discussed below in the section entitled "For Conditions Outside 14 CFR Part 25, Appendix C."

Uncertainties in tunnel operating conditions depend on individual instrument calibrations, typically observed differences between instruments when an average reading from more than one is used, and uncertainties in the calibration maps used to establish spray-bar air and water pressures. In addition, conditions vary somewhat over the spray period and average conditions are reported. For the IRT, the following uncertainties have been estimated [17, 18] for the instruments and calibration techniques used: temperature, ±1.5°F; airspeed, ±4 percent; MVD, ±12 percent; and LWC, ±12 percent. The MVD and LWC figures are uncertainties at the center of the test section. These uncertainties are estimates for one tunnel using one set of instruments. They do not include tunnel-to-tunnel differences or variations among different types of instrument. Estimates of the uncertainties for other icing wind tunnels have not been reported, but are probably not markedly different from these. A brief description of the sources for the uncertainties within a given tunnel is given in the following paragraphs.

The total temperature in the IRT is recorded as the average of 24 type T thermocouples located at various positions on the downstream plane of the turning vanes at corner D. Corner D is located just upstream of the spray bars. In one study, a Rosemount total-temperature probe in the IRT test section gave temperatures that agreed with the IRT corner-D average within ±0.5°F [17]. Leading-edge thermocouples on a model have also shown very good agreement with the tunnel averages [19]. Additional confidence that the IRT corner-D average total temperature is close to the actual test-section total temperature has come from observations of the effect of the indicated total temperature on ice accretion. Figure 3 shows the results of a sequence of three icing tests [20] with total temperatures of 28°, 30°, and 32°F. While ice accreted at the leading edge of the model for an indicated total temperature of 28°F, less accreted at 30°F, and none accreted at 32°F. The observed trend of the effect of temperature on quantity of ice accreted is



(a) Total Temperature, 28°F (b) Total Temperature, 30°F (c) Total Temperature, 32°F

FIGURE 3. EFFECT OF TEMPERATURE ON ICE SHAPE (21-IN-CHORD NACA 0012 AIRFOIL AT 4° ANGLE OF ATTACK; AIRSPEED, 130 MPH; MVD, 20 µM; LWC, 1.3 G/M^3; AND TIME, 8 MIN [19])

consistent with what one would expect for these temperatures; thus, the actual total temperature is apparently close to the indicated values. The estimated MVD uncertainty quoted on page 8 is that for a single measuring system. There is no standard instrument for measuring MVD; thus, an absolute uncertainty in MVD cannot be given. In 1983, Olsen, et al. [19] compared several kinds of drop-sizing instruments against a cloud calibration based on predicted droplet trajectories. They found that the instruments agreed only within ±30 percent of the calculated drop size (±6 µm for a 20-µm MVD). Furthermore, drop-sizing instruments require skilled operators to interpret and analyze the droplet distribution data to arrive at a reported MVD. Thus, different operators using the same instrument might report different MVDs for the same cloud. For a single instrument and operator, uncertainties in sizing and counting droplets have been estimated from data scatter observed when drop size is calibrated as a function of nozzle air and water pressures. Because of evaporation, low humidity environments would tend to remove very small droplets from the distribution. Thus, the effect of evaporation on MVD is greatest for clouds with very small MVDs. Humidity is not a controlled parameter in existing tunnels, but in closed-loop tunnels it tends to reach a steady-state value with time. This effect is probably not large in closed-loop tunnels for MVDs greater than 15 µm.

Uncertainty in LWC has two main sources. First, the ice thickness measurements used to calibrate the tunnel LWC involve some experimental error. These data typically fall within ±10 percent of a curve fit of the results, with the bulk of the data within ±5 percent. Second, models used in tunnel testing produce blockages different from that produced by the calibration blade. How blockage may affect LWC has not been systematically studied, but models that distort the flow such that the cloud moves from its calibration position will change the center value of LWC. The uniform region of the cloud is defined as one in which LWC varies by no more than ±20 percent from the center value. Therefore, in addition to the estimated uncertainty at the center of the test section, within the uniform region LWC variations of ±20 percent can be expected.

Finally, evaporation has been estimated to reduce the LWC by as much as 0.1 to 0.15 g/m^3 in closed-loop tunnels [21] and perhaps more in open-loop tunnels. Actual values are dependent on air humidity, which tends to reach saturation in closed-loop tunnels. Because dry atomizing air is injected with the spray, the evaporation effect increases with air pressure. The effect of evaporation on LWC uncertainty is clearly greatest for low values of LWC.

The lack of standard techniques and instrumentation for the calibration of tunnels raise questions about the comparability of simulated clouds from one tunnel to another. There is no assurance that the MVD, LWC, or uniformity of a cloud measured in one tunnel are the same as for a cloud with the same reported MVD and LWC in another facility. There are also differences between tunnels in the flow angularity, turbulence level, and droplet temperature that may affect ice shapes. Consequently, shapes measured in two facilities with the same apparent cloud conditions may not agree.

Repeatability

Repeatability of an icing wind tunnel is demonstrated by periodically measuring the LWC and the icing cloud uniformity in the test section. It is customary in the IRT to perform limited calibration tests to check cloud repeatability about every 6 months or after a change in one of the three tunnel systems that might be expected to influence the cloud: the low-speed wind tunnel, the spray bar system, or the refrigeration/heat exchanger system. After a major tunnel change, full cloud calibrations are made. The calibration method has been described above (see the section entitled "Cloud Calibration, Uniformity and Calibration Accuracy"). No hard criteria exist for acceptable repeatability, but in the IRT if no change to any of the major tunnel systems has been made, the LWC calibration for the center of the test section is expected to repeat for each nozzle set within 2 or 3 percent. For the lowest speed for which a calibration is made, 50 mph, the repeatability may not always be as good as ±3 percent, but if the agreement with previous calibrations is good at higher speeds, the repeatability is considered acceptable. This periodic examination for changes in cloud calibration can reveal important problems, such as dirty nozzles, that should be corrected before testing continues.

Icing wind tunnel operators also record and compare ice-accretion shapes as an indicator of cloud repeatability. Ice shapes on an airfoil are recorded before and after any significant modification and calibration of the wind tunnel. As with the icing cloud uniformity measurement, no standard exists which defines acceptable ice-accretion shape repeatability. As such, the comparison of ice shapes is left to the tunnel operator and is inherently qualitative and subjective. Figure 4 gives examples of ice shape repeatability from the IRT.

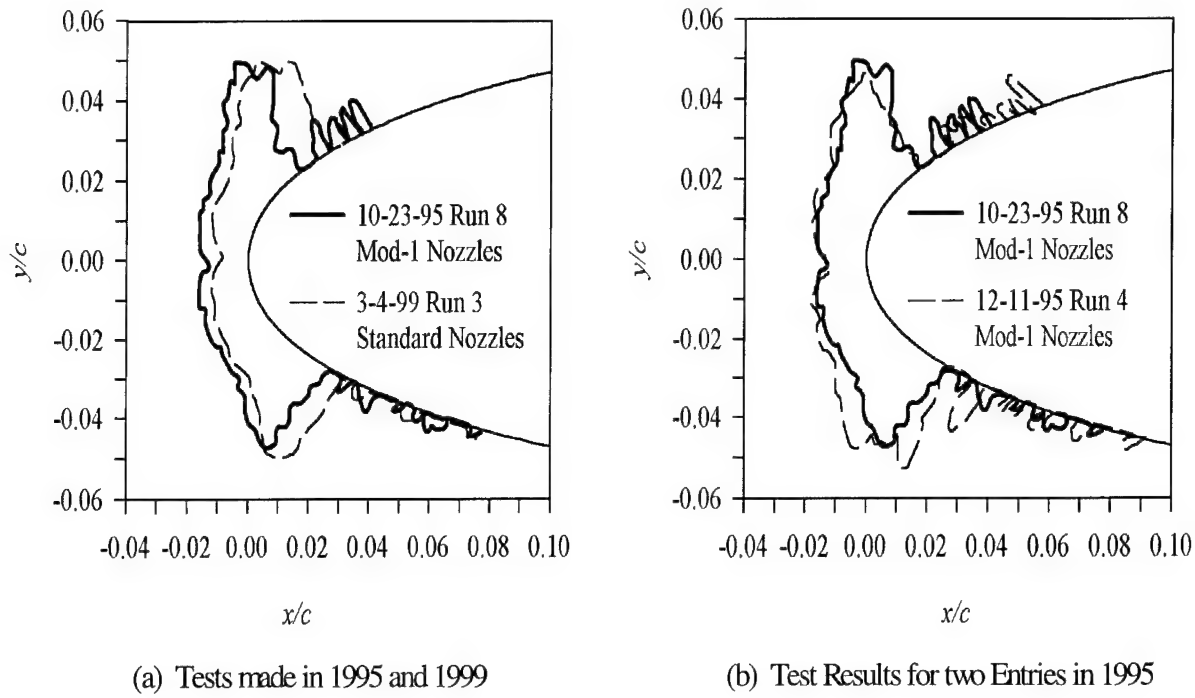


FIGURE 4. ICE SHAPE REPEATABILITY IN NASA GLENN IRT (21-in chord NACA 0012 airfoil at 0° angle of attack; static temperature, 20°F, airspeed, 150 mph, MVD, 30 μm; LWC, 1 g/m^3; and time, 7.3 min)

Figure 4(a) compares ice shapes recorded in the IRT on a vertically mounted NACA 0012 airfoil during separate test entries at the same set conditions. The first shape was taken in October 1995, the second in March 1999. Between these two entries, the entire IRT spray-bar system was replaced and the cloud recalibrated. The ice shapes shown are from a position at the tunnel center and were traced by hand. The two ice shapes appear to agree well but are displaced slightly relative to the model. Although different nozzle sets were used for the two tests, the two types of nozzles have been shown in other studies to have little effect on ice shape. For example, figure 5 compares results of tests made with both nozzle sets for rime and glaze ice.

Results for tests made in October and December 1995 are shown in figure 4(b). No changes to tunnel systems were made between those two tests. The ice shapes again show very good agreement with only small changes in the horn positions. Generally, repeatability of ice shapes for the same entry is of the quality shown in figure 4(b). For different entries, the differences in shape can occasionally be more pronounced than those shown. For tests for which ice shapes are critical, it is advisable to repeat the spray to record more than one shape on different days. Factors which affect ice-shape repeatability are not fully understood, but probably include small shifts in the cloud location, changes in ambient conditions such as humidity, differences in the model installation from entry to entry, and variations in individual spray nozzle flow characteristics.

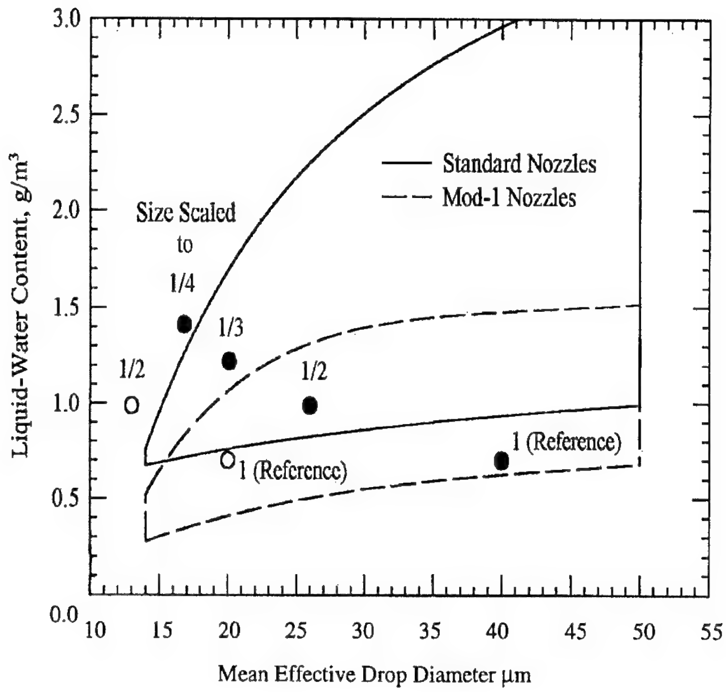


FIGURE 5. SCALING CONDITIONS AND ICING TUNNEL CLOUD, AIRSPEED, 150 mph; SCALING USING RUFF METHOD WITH CONSTANT VELOCITY

An exception to the generally good repeatability of ice shape occurs at temperatures near freezing, or with any set of conditions which give very low freezing fractions, because the ice shape is very sensitive to temperature when the freezing fraction is low. This was shown in figure 3, which gave the results of a sequence of three icing tests [20] with total temperatures of 28°, 30°, and 32°F. The quantity of ice accreted at 30°F was less than at 28°F because some water ran back on the model without freezing at the higher temperature. When the test was run at 32°F, no ice formed on the leading edge. Thus, if several tests at 30°F were made, small differences in temperature from one test to another could result in significant differences in the quantity and shape of the accreted ice.

Ease of Use

Compared with flight, icing wind tunnels provide relatively easy and precise control of temperature, airspeed, MVD, LWC, and spray time, and for some tunnels, test section pressure. Because of the ability to set and stabilize conditions rapidly, icing tunnels permit a large number and wide range of test conditions to be explored in a short time. Direct, close-up observation of the model during the icing spray provides insight into accretion processes and ice-protection system operation, and testing plans can easily be modified during the test to explore observed phenomena. Observation windows make it possible to take video and still photographic records from the comfort and safety of the control room during the test. In addition, for pressures simulating sea level, the ability to enter the test section immediately after a test allows ice shapes to be examined, photographed, and measured as needed. Most facilities provide personnel for operating the tunnel and may provide some guidance in developing test matrices.

Scaling to Extend Effective Tunnel Capability

This section provides only a brief review of scaling. More detailed discussions including descriptions of additional scaling methods are given in references [5, 6, 7, and 18].

Scaling methods can be broadly divided into two types: (1) Scaling of test conditions with a full-size model when the desired airspeed, MVD, or LWC is outside the operating envelope of the tunnel. This type of scaling was discussed in the section entitled "Range of Capabilities" above. (2) Scaling of model size for situations in which icing tunnel test sections cannot accommodate full-size models. Methods to scale model size may require testing with altered cloud conditions to insure that various similarity parameters are matched between the scale and reference, or full-size, test. In the next few paragraphs, methods to scale model size will be reviewed. As noted in the section entitled "Range of Capabilities," the usual goal of a properly scaled test is to produce an ice shape which has the same nondimensional coordinates as would occur if the reference, or full-size, model were tested. There may be other goals as well, such as determining aerodynamic penalties of ice or studying ice-protection system operation; but this discussion will be limited to scaling to simulate full-size ice shapes.

There are two basic approaches to scaling model size: (1) model scaling in which the entire model has the same dimensionless coordinates as the reference, but with a smaller chord, and (2) hybrid scaling, in which the leading edge of the model is maintained full size, but a truncated chord with an adjustable flap is used to duplicate the full-size airfoil flow and pressure distribution over the leading-edge section.

Model-scaling methods are based on the same similitude principles used in test-condition scaling discussed in the section entitled "Range of Capabilities." With the scale size selected, the temperature, airspeed, MVD, LWC, and icing time must be determined for the scale test. The matching of six similarity parameters between the scale and reference (desired) icing encounters provides six equations that can be solved simultaneously to yield the test conditions for the scale test. In tunnels without pressure control, such as the IRT, only five similarity parameters are needed.

Bilanin identified 18 dimensionless parameters related to the physics of ice accretion that could be included in a rigorous icing scaling approach [22]. Clearly, then, more parameters are available than are needed. Work is still in progress to identify which parameters are the most important. The Ruff scaling method [7] determines five of the six test conditions by matching the scale and reference droplet trajectories, ice accumulation, and three heat-balance parameters. In this method, the user chooses the scale airspeed.

For use in atmospheric-pressure tunnels, the Ruff method has been modified by neglecting one of the heat-balance parameters, with scale airspeed still selected by the user. The scale airspeed can be obtained in a number of possible ways, including matching the reference airspeed, matching the scale and reference Weber numbers, or matching the Reynolds numbers. Some results indicate that more faithful scaling of ice shapes is achieved by the use of scaling parameters, such as Weber number or Reynolds number, which result in scale velocities higher than the reference value [18]. Tests have been performed using the Ruff method with a constant Weber number with some success at scales as small as 1/3 of the reference size.

To evaluate a scaling method it is necessary to test a model with a set of reference conditions, apply the scaling method to determine appropriate test conditions for a particular scale, and perform the scale test. The resulting ice shapes for reference and scale can then be nondimensionalized and compared. Most tests are made for model scales of 1/2 size, but some have been made for greater size reductions. It is difficult to test scaling methods for scales much less than 1/3, however, because as the scale is reduced, there are fewer reference conditions in the tunnel envelope that have corresponding scale conditions also within the envelope.

This point is illustrated in figure 5. This figure uses the 1998 IRT cloud calibration. The cloud for this tunnel was recalibrated in 2000, but results were not finalized by the time of the writing of this article. In the first example, shown with solid symbols in the figure, the reference test has an airspeed of 150 mph, an MVD of 40 μm, and an LWC of 0.7 g/m^3. The Ruff scaling method with constant velocity (scale and reference conditions maintain the same airspeed) was used to determine the scale conditions: at 1/2 scale, the MVD should be 26 μm and the LWC, 1 g/m^3; at 1/3 scale, the MVD should be 20 μm and the LWC, 1.2 g/m^3; and at 1/4 scale, the MVD should be 17 μm and the LWC, 1.4 g/m^3.

Figure 5 shows that the reference test can be made with Mod-1 nozzles, the 1/2-scale test with either nozzle set, and the 1/3-scale test with the Standard nozzles. The 1/4-scale test cannot be run in the IRT with the existing spray system at this airspeed. In performing scaling tests, it is desirable to make as few changes to the tunnel as possible to insure good comparability between tests. Although figure 5 showed that, for the IRT, the clouds from the two nozzle sets are equivalent, the use of different nozzle sets to generate clouds for scaling tests provides a less controlled sequence of experiments than if the same nozzle set were used throughout. Thus, even the 1/3-scale tests for this example would involve additional uncertainties in the validity of the ice-shape comparisons.

The second example in figure 5, shown with open symbols, is for a reference case with a 20-μm MVD. For this case, 1/2-size scaling would dictate an MVD of 13 μm and an LWC of 1 g/m^3, which fall outside the capability of the spray system at 150 mph. To permit the scale tests to be performed, the scale test conditions determined by the Ruff method would themselves have to be scaled in a two-step process. First, model size scaling is applied by matching five similarity parameters (or six for an altitude tunnel), then one of the resulting scale test conditions is given a new value to provide compatibility with the tunnel operating envelope. One of the test condition scaling methods, using only three or four similarity parameters, is then applied to find the final test conditions. Because the final step relaxes the similarity requirements, this approach introduces further uncertainties into the already approximate nature of the scaling. Limited testing using the Olsen method as the last step was found to work well for small changes in test conditions [6].

These examples of the problems in evaluating scaling methods also demonstrate some of the limitations of using model scaling methods within the current capabilities of icing tunnels. For example, if it were desired to use a half-scale model to simulate tests with a reference model too large for the tunnel, figure 5 shows that for an airspeed of 150 mph,

reference conditions with an MVD of around 20 μm could not be simulated without applying test-condition scaling.

Although model scaling can be applied with relatively simple sets of calculations and scale model design is straightforward, this approach cannot include similarity parameters that might be important to icing. Thus, the scaled ice shape may sometimes be only an approximate simulation of the full-size accretion. In addition, the limited operating map of a tunnel makes it difficult to apply model scaling in some situations.

The second approach to scaling is known as the hybrid method [23, 24, and 25]. It avoids the problems in model scaling by relying on the fact that icing phenomena occur primarily at or near the leading edge of an airfoil. Thus, if the leading-edge region is maintained full size, no scaling calculations need to be applied provided the flow field in the leading-edge region and droplet trajectories of the test are the same as would be experienced by the reference wing section in the icing encounter to be simulated. The hybrid method, then, maintains a full-size leading-edge region with a subscale aft section to reduce the blockage. The flow field and trajectory matching is accomplished by applying aerodynamic and droplet-trajectory codes to design the new aft section. The addition of an adjustable flap permits flow field adjustments for testing with a range of angles of attack, but the fundamental disadvantage of this method is that the aft-section design is only valid for a specific flow and droplet-size condition. Thus, to test over a range of icing conditions, multiple aft sections need to be designed and fabricated. The method has received limited testing using half-scale models at one speed and one MVD with encouraging results [25]. In principle, smaller scales should be possible as well, but the amount of blockage reduction is limited by the use of the full-size leading-edge portion. Further evaluation of hybrid scaling is needed both to validate the approach for a wide range of conditions and to define possible limitations in the use of the flap. To achieve greater reductions in scale size, some combination of model scaling with hybrid scaling may prove be advantageous.

Design or Certification Requirements Being Met in Tunnel

Tests for support of certification may involve demonstration of ice protection systems over the range of the 14 CFR Part 25, Appendix C envelope, accretion of ice shapes to establish critical conditions, and verification of analytical predictions. Molds of ice shapes produced in the tunnel can be made and the shape then reproduced in a durable medium either for flight tests or for study in an aerodynamic tunnel. The tunnel is able to produce conditions which are difficult to find in nature and which would therefore be very time-consuming and expensive to obtain with flight tests. To obtain data for certification, the procedure is typically to do analysis and icing tunnel tests at a range of conditions, including those not usually encountered in flight, then perform limited flight tests to validate the analysis and tunnel results.

Military qualification for flight in icing conditions can similarly be done more efficiently and safely by supplementing limited flight tests with more extensive tunnel tests and analysis.

LIMITATIONS OF CURRENT ICING TUNNEL SIMULATION METHODS

How Well do Tunnels Function With Respect to Their Stated Purpose?

Icing tunnels are intended to provide a simulation of natural icing conditions in a controlled and safe testing environment. While a large portion of the 14 CFR Parts 25 and 29 Appendix C is generally simulated by icing tunnels, there are some significant limitations in the ability of icing tunnels to simulate all natural icing encounters. These include

- Appendix C conditions are not fully covered.
- Heat exchangers, spray-bar systems, and walls affect test-section airflow; thus, the free stream flow angularity and turbulence in the test section may not match natural flight.
- Test section size and cloud size limit the model size and sometimes the type of test.
- Scaling methodologies are not fully developed.
- No nonintrusive, on-line LWC profile measurement techniques exist.
- Airspeeds are limited; this is especially a problem for rotorblade tests.
- Calibration for freezing drizzle conditions is not complete.
- Cannot simulate rain or freezing rain with existing equipment.

Some of these issues will be discussed in more detail in the sections that follow.

How Well Does Method Simulate Natural Icing Encounters?

One of the fundamental questions regarding ground simulation facilities is whether they produce the same ice shape and aerodynamic penalties which would be experienced in a flight icing encounter at the same conditions. The difficulty in trying to perform such a comparison is that the natural icing cloud is not spatially or temporally uniform with respect to either LWC or MVD. LWC can be particularly variable, and aircraft flying through a cloud experience conditions that fluctuate significantly. Aircraft angles of attack and sideslip angles can also change with time. Thus, it is inherently difficult for icing tunnels to closely simulate the exposure history of flight through a natural cloud. Attempts to compare flight with tunnel results are usually made with flight conditions (LWC and drop sizes) averaged over the exposure time. In flight, however, the varying LWC can produce ice growths that are composites of rime accretions (low LWC) at times and glaze accretions (high LWC) at other times. Such an accretion would probably not look the same as a tunnel accretion at an average LWC.

Hansman and Kirby [26] attempted comparisons of flight and IRT ice growth on cylinders. They faced the varying LWC problem in flight, and thus, could obtain only limited data. They did conclude, however, that there were differences in the ice growth consistent with higher heat transfer rates in the tunnel compared with flight. Several unpublished studies by NASA Glenn researchers in the 1980s and '90s have also attempted to compare IRT results with flight icing encounters, but with unacceptable uncertainties in the data. In summary, although some limited data exist, there are not

enough flight results in which cloud conditions are sufficiently steady to permit meaningful comparisons of flight ice shapes with tunnel shapes.

Icing tunnels typically have a high turbulence level compared with flight. Although turbulence levels in natural icing clouds have not been measured, they are assumed to be low. In icing tunnels, the spray bars and supporting structures add turbulence, and not all tunnels use screens to reduce turbulence levels. The IRT, for example, does not use a screen. Higher turbulence tends to assist in mixing of the spray and should therefore help with respect to cloud uniformity, but it probably does not simulate nature. For velocities less than 300 mph, the turbulence intensity in the IRT has been measured by several researchers to be 0.5 to 0.9 percent without the spray bars operating [27], compared with values of less than 0.1 percent in flight outside of icing conditions [28]. With a spray, the IRT turbulence intensities can be 50 percent higher than with none [27]. An increase in turbulence can affect both aerodynamics (increasing skin friction and moving the boundary-layer transition location forward) and icing (increasing local convective heat transfer rates.) Comparisons of flight and IRT heat transfer measurements were made by Gelder and Lewis [29] and by Poinsatte [28]. Both studies showed higher heat transfer rates in the tunnel than in flight. Furthermore, heat transfer rates in natural icing clouds may vary from cloud to cloud [26]. The turbulence levels, and resulting heat transfer rates, in icing tunnels would appear to impose an inherent limit to their ability to simulate nature fully. Considerably more study is needed, however, to determine how important the differences between flight and tunnel are. Actual conditions in nature need to be defined better, and natural and tunnel ice shapes and effects of ice need to be compared for varying LWC conditions.

How Well do Tunnels Perform With Respect to Desired Functionality?

For 14 CFR Part 25, Appendix C Conditions

Although icing tunnels use air-atomizing nozzles to allow somewhat independent control of water flow rate and droplet size, existing water spray nozzle technology does not permit total independence of the achievable LWC and MVD ranges. Consequently, the LWC and MVD capabilities of icing wind tunnels are limited in some ranges. For example, figure 2 showed the map of the IRT operating conditions superimposed on the 14 CFR Part 25, Appendix C envelope. Although this figure is for the IRT, it demonstrates how the spray from air-atomizing nozzles typically used in icing tunnels fails to reproduce portions of the natural environment. Specifically, icing wind tunnels cannot meet the high LWC, small MVD portion of the intermittent maximum icing envelope and conversely, cannot reproduce the low LWC, large MVD part of the Appendix C envelopes. In addition, the portion of the Appendix C envelope simulated is dependent on airspeed. In principal, the use of a greater number of spray nozzles could increase the LWC obtained for low MVDs. While additional spray bars and nozzle locations could be designed into spray-bar systems, it would be difficult to accomplish the large increase in numbers needed without greatly complicating spray-bar systems and without increasing the flow blockage and flow distortion.

The section entitled "Cloud Calibration, Uniformity, and Calibration Accuracy" discussed some of the limitations in icing tunnels with respect to cloud calibration and

instrumentation standards. Consistent calibration techniques and measuring instruments for all tunnels would improve the comparability of icing clouds among different tunnels.

One of the limitations in producing low LWCs is the stability of the tunnel environment for such conditions. Although, in theory, an LWC of 0.1 g/m^3 might be possible with present spray systems, uncertainties in LWC are on the order of 0.1 g/m^3 due to evaporation. Thus, the true LWC at such low levels is highly uncertain.

The effects of the cloud limitations are different for different types of tests conducted in an icing wind tunnel. In the case of ice protection system (IPS) development and certification, the effects on a mechanical IPS are markedly different than for a thermal IPS. Thermal anti-icing systems' power requirements tend to increase with LWC. Therefore, testing at higher LWCs provides more conservative results, that is, indicates that higher power is required than might actually be needed. Since most of the heat requirement for thermal IPS balances the convective heat transfer, testing at low temperatures (-22°F) is essential. If the low temperature cannot be simulated, testing at higher temperatures but also with higher LWCs can be performed by scaling to maintain the same heat load.

Mechanical ice protection system operation is dependent both on the type of ice (glaze, mixed, or rime) and on the ice thickness. The type of ice is affected primarily by temperature and LWC, and the thickness can be controlled in the wind tunnel environment by varying LWC or exposure time.

The section entitled "Scaling to Extend Effective Tunnel Capability" discussed scaling methods and current limitations of tunnels that make it difficult to validate scaling methods or to perform scaled tests for models scaled to 1/3 reference size or less. One of the basic problems is that the existing nozzles cannot produce the small droplet diameters at the LWCs that scaling to these sizes requires. The capability to produce clouds with droplet sizes below 10 μm along with an LWC range covering several tenths of a g/m^3 should be an eventual goal of icing tunnels to permit validation of scaling methods. One potential problem with trying to produce MVDs much smaller than 10 μm is the effect of evaporation, which may be significant for drop sizes of a few microns and for low LWCs. This issue will require additional study.

Cloud nonuniformity may affect the results of some tests, and the size of the uniform cloud may impose restrictions. The calibrated LWC for the given spray-bar air and water pressures is the value at the test-section center. The uniform icing cloud is usually defined as that portion within which the LWC varies by no more than ±20 percent of the value at the center of the tunnel test section. The size of the uniform cloud varies with airspeed and LWC, and, for some tunnels, may cover only half the test section cross section, with LWC falling off toward the walls. For tests with airfoils of uniform chord, results are often considered only at or near the test-section center. For swept wings, rotating blades, or engine inlets, however, the cloud uniformity may be a problem. Changes in blockage from the calibration configuration may change flow patterns and thus the position of the uniform cloud and give an LWC at the test-section center, which is somewhat different from that calibrated. Such effects have been the subject of only very limited studies, and need to be considered as part of future tunnel calibration work.

Frost formation on models has not been adequately addressed and is not well understood at this time. Frost formation has been observed in tunnels under conditions for which it has not been reported in flight. It is probably a result of the high saturation of the test-section air under some conditions in icing tunnels. The IRT test section, for example, is supersaturated at airspeeds above about 200 mph [30]. For high speeds, a condensation cloud can be seen as the flow enters the test section before the spray is turned on. Frost can be an issue for drag measurements in an icing tunnel and is usually handled by cleaning the model aft of the main ice shape before drag is measured.

For Conditions Outside 14 CFR Part 25, Appendix C

Supercooled large drop conditions include both freezing drizzle and freezing rain. Freezing drizzle drop sizes range approximately from 50-500 μm, while freezing rain drops can have diameters of 500-1500 μm. These two size ranges will be discussed separately.

For MVDs up to about 200 μm, the primary limitation of icing tunnels is in the lack of calibration that has been performed to date, rather than an inherent inability to produce these conditions. The calibration effort has not been pursued because there has been little demand in icing tunnels for these conditions since at present there are no certification requirements. In addition, information on the ranges of droplet size, size distributions, and LWC levels which occur in nature for SLD is not yet well defined. Other limitations with respect to SLD may result from individual tunnel configurations. For example, tunnels with short, rapid contractions into the test section will experience separation of larger droplets from the full cloud, thus causing icing at the contraction surfaces, distorting the drop-size distribution in the test section, and causing the uniform cloud size to shrink. Larger tunnels, such as the IRT and BRAIT, are much less susceptible to this problem because of the lower acceleration of droplets through the contraction; nevertheless, for all icing tunnels, the size of the uniform cloud decreases with increasing droplet size. For the IRT and BRAIT, the maximum practical MVD to avoid the effects of large droplet separation might be on the order of 200 μm, while for smaller tunnels, it could be as little as 100 μm. Gravitational effects are probably less important than the effects of acceleration through the contraction.

An additional SLD-related problem could be caused by the low air and water pressures required to produce large droplets. Some tunnels can experience water-pressure head differences between the upper and lower spray bars, and these differences in pressure introduce additional variation in the LWC and droplet size uniformity. When the model, such as a wing section, is mounted horizontally, the head difference should have little effect on the cloud near the center of the test section, however. The IRT and BRAIT control pressures separately for each spray bar to avoid this problem. Finally, the issue of supercooling of large droplets was discussed in the section entitled "Cloud Calibration, Uniformity, and Calibration Accuracy" where evidence was given for the larger tunnels, that droplets up to at least 170 μm in diameter are probably near the ambient test section temperature.

The drop-size distribution of large droplets has been measured in the IRT [16]. In figure 6, the distribution for a 160-μm MVD cloud (solid symbols) is compared with that for a typical 14 CFR Part 25, Appendix C cloud (open symbols) [10]. The vertical axis is the LWC contained in droplets of a given size normalized by the bin width of the instrument. As discussed above in the section entitled "Cloud Calibration, Uniformity, and Calibration Accuracy," the complete dropsize distribution in the IRT is obtained by using two instruments with different size ranges and combining the results to produce a single distribution. Because the bin widths of the two instruments are different, the normalizing of the LWC with respect to bin width permits the data from the two to be plotted as a single distribution. In this plot, the FSSP probe contributes data for drop sizes less than 50 μm, and the OAP for drop sizes greater than 50 μm. The 160-μm-MVD cloud has a flatter distribution and includes much more water in drop sizes larger than 40 μm than that of the 23-μm-MVD cloud. It was noted in the section entitled "Cloud Calibration, Uniformity, and Calibration Accuracy," that unpublished data indicated good agreement of the IRT Appendix C dropsize distribution with one natural cloud distribution. A natural-cloud distribution for a 112-μm MVD has been reported by Ashenden and Marwitz [31]. That distribution is similar to the 160-μm IRT distribution but with no droplets reported above 300 μm. Other studies are presently characterizing natural clouds for freezing-drizzle conditions. As with Appendix C conditions, distributions for large droplets are not unique for a given MVD, so comparison of tunnel and natural clouds is difficult. It should be noted, too, that there is considerable discussion about whether MVD is even an effective way to characterize large-droplet clouds. Because the icing limits for a large-droplet encounter are farther back on the airfoil than for Appendix-C-sized clouds, a more meaningful descriptor of the cloud might give more weight to the larger drops than the MVD does. At this time, no standard characterization has emerged.

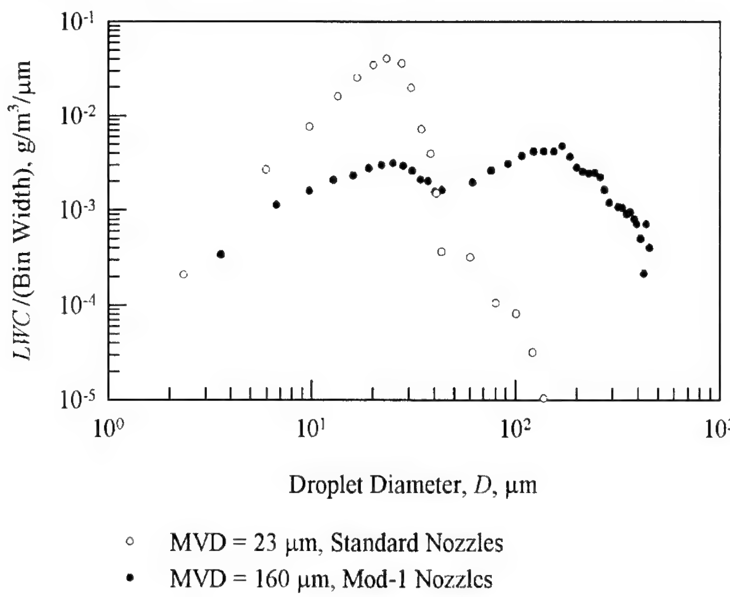


FIGURE 6. SAMPLE DROPLET SIZE DISTRIBUTION FOR 14 CFR PART 25, APPENDIX C AND LARGE DROPLET CLOUDS (IRT)

Freezing-rain conditions may not be achievable in icing tunnels. Studies of the aerodynamic effects of rain have used oscillating spray systems to produce the large drops and LWC requirements simultaneously [32]. To prevent separation of the large droplets from the cloud as it passes through the contraction and to avoid gravity effects, these systems would probably have to be located at the entrance to the test section. To insure the droplets were supercooled would additionally require that they be precooled to near the air temperature before injection. Without further analysis and experimentation, it is not clear whether spray systems to produce freezing rain are at all feasible for icing tunnels.

Mixed-phase (supercooled liquid water droplets mixed with frozen ice crystals) cloud conditions are common in the atmosphere [33, 9]. Operation of both IPS and engines in mixed-phase conditions are addressed in certification under the European Joint Airworthiness Regulation (JAR). They have been simulated in icing tunnels to a limited extent (see the section entitled "Range of Capabilities"), but further study is needed to establish if desired solid/liquid ratios with uniform clouds can be obtained repeatably. Furthermore, instrumentation to characterize particle size and phase requires further development. In particular, there is a need to distinguish between liquid and solid water particles when the particles are spherical. Finally, there has been little work to characterize natural mixed-phase clouds. Also lacking is an understanding of how well natural conditions need to be simulated for tunnel tests to address safety issues. Such information is necessary for tunnel developers to know how best to simulate mixed-phase and glaciated conditions.

Turbine engines of certain designs operating in mixed-phase conditions have experienced malfunction due to flow blockage or flame out of the combustor. This has been caused by the penetration of ice crystals deeply into the engine where they melt in air now warmed by the first stages of the compressor. These particles can then refreeze to accrete ice on cold internal engine parts further downstream that typically are not considered ice accumulation sites during normal 14 CFR Part 25, Appendix C icing tests. Testing of these icing conditions is an engineering challenge due to the difference between the local air temperature, which can be quite warm, and the icing particle temperature at the component. This temperature mismatch has to be achieved in the test facility to simulate the heat balance on the surface of the component. Because icing wind tunnels operate with airflow at subfreezing temperatures, they cannot simulate this kind of mixed-phase encounter.

Snow is very difficult to simulate in an icing tunnel because of the large time required to form a realistic simulation of a natural snowflake. However, experience indicates [34] that some effects can be simulated with partially-frozen droplets. For example, thermally protected surfaces can be reliably tested in this way. Evaporative thermal IPS heat requirements are determined primarily by the total water content rather than the state of the water (liquid or solid), while for running-wet systems the state is important. Snow simulation requirements for these and other applications need further study to define testing requirements.

GAP ANALYSIS FOR ICING TUNNELS

Icing tunnels allow the relatively strict control of icing parameters for detailed investigation of icing phenomena related to design and certification of aircraft. The cost and scheduling requirements of tunnels, combined with their limited numbers across the country, preclude their use in everyday design work. Their value is due to the accuracy of results, and they are particularly useful during checkout of designs, investigation of problems, and certification. The role of icing tunnels is similar in many ways to the current use of wind tunnels to validate and supplement computational fluid dynamics (CFD) analysis.

Some gaps exist with regard to operation at the low-MVD, high-LWC conditions within the 14 CFR Part 25, Appendix C envelope. There are other gaps which relate primarily to operation at conditions outside of Appendix C. These include SLD, mixed-phase, and fully glaciated conditions. Although there are specific tunnel limitations for many of these conditions, another problem in each area is the lack of atmospheric characterization data, lack of understanding as to how well nature must be simulated, and lack of specific regulations requiring testing at such conditions.

The purpose of the simulation gap analysis is to identify capabilities currently unavailable but desired in simulation tools and facilities.

Applications

During the design phase, tunnels are useful in determining component ice accretion including ice shape, size, location, and roughness, as well as troubleshooting problem areas. Tunnels are also needed to validate the results of icing codes on which certification efforts are based. Other certification roles involve ice protection system validation, artificial shape generation, aircraft performance testing, and investigation of unexpected/problem ice accumulations.

Strengths

Some of the important strengths from the manufacturers' viewpoint for design and certification are:

- Repeatability
- High degree of control of test conditions
- Rapid acquisition of test data
- Low cost compared with natural flight testing
- Year round availability

Desired Improvements

The most significant desired improvements for tunnels are expansions of simulated conditions to permit increased coverage of 14 CFR Part 25, Appendix C. Expanded calibration of SLD capability for freezing drizzle will soon be required for certification testing. Freezing-rain, snow, and mixed-phase capability may not be practical for icing tunnels in the near term and do not represent the primary type of testing required in a tunnel. Some issues are related to improving the quality of the testing environment, such as reducing flow angularity. Other goals depend on instrument development, including the provision of nonintrusive measurement of cloud conditions during a spray.

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CAPABILITIES AND LIMITATIONS OF ICING SIMULATORS IN THE SIMULATION OF ICING CONDITIONS FOR THE DESIGN AND CERTIFICATION OF AIRCRAFT AND ENGINES

Tankers

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GENERAL

This section presents brief descriptions of known U.S. icing tankers, their capabilities (strengths), limitations on their use, and some of the uncertainties associated with in-flight icing simulations. Attributes of both government owned and privately owned tanker aircraft are discussed.

BACKGROUND

Both the government and private companies have used water spray tankers to produce an artificial icing cloud for simulation of natural icing conditions. The most extensively used tanker was a modified NKC-135A aircraft, USAF S/N 55-3128. This tanker was used to evaluate anti-icing/deicing systems and other critical areas such as engine inlets of all new military aircraft over several decades. This tanker was retired in 1995 for various reasons, the most significant being the high cost of operation due to low utilization rates. An effort is currently underway to replace it. Other water spray systems used for icing cloud generation include a modified T-47 owned by Cessna Aircraft, a Cessna Citation II aircraft which was modified for Lockheed-Martin by Cessna Aircraft Company, a Raytheon (King Air) tanker, and the U.S. Army helicopter icing spray system (HISS).

Aircraft anti-icing and deicing systems are normally designed to operate in natural icing conditions with droplet sizes and liquid water content as described in Title 14, Code of Federal Regulations (14 CFR) Part 25, Appendix C. These envelopes represent a majority of the icing conditions around the world which are encountered by aircraft; however, a very small percentage of icing clouds contain supercooled large droplets (freezing drizzle and freezing rain), which can be extremely hazardous for some types of aircraft. How well existing tanker icing spray systems can duplicate natural conditions is the focus of this paper.

AIR FORCE ICING TANKER

Description

The NKC-135A, S/N 55-3128, was an aerial refueling tanker modified to perform water spray missions for both in-flight icing and in-flight rain evaluations of new and modified United States Air Force (USAF) aircraft. This aircraft was first modified in the late 1950s to perform these missions. Beginning in 1987, it was upgraded in an effort to correct spray tanker deficiencies and to improve cloud physics. This upgrade also provided for dual use of the tanker for uninstrumented air refueling of local test sorties at Edwards Air Force Base (AFB).

In the water spray configuration, the forward body fuel tanks were capped and separated from the remainder of the fuel system and were filled with 2000 gallons of demineralized water. This was enough water for about 2 1/2 hours of testing, depending on the flow rate selected. Bleed air from the number 2 and 3 engines was used to prevent the water in the array and around the nozzles from freezing, and for atomization of water from the nozzles to obtain the desired cloud physics characteristics. Both the water and bleed air were routed aft through the fuselage to the back bulkhead, and then through a modified aerial refueling boom to a circular nozzle array. A new square array was built concurrently with the tanker upgrade and was interchangeable with the circular array.

The airspeed and altitude ranges for in-flight icing testing using the circular array were 150 to 300 knots indicated airspeed (KIAS) and 5,000 feet above ground level (AGL) to 30,000 feet pressure altitude (PA). A laser distance measuring system (LDMS) and video camera were mounted in a pod in the aft fuselage area. The LDMS was used to maintain the desired separation distance between the tanker and the system under test. The video camera provided a real-time display of the system under test through a monitor mounted on the operator's console. The water spray system was controlled from an operator's console located in the mid upper-deck area of the fuselage, except for water flow control and purge valves, which were operated from the boomer's compartment. A more detailed description of the upgraded Air Force NKC-135 tanker water spray system is presented in AIAA technical paper 93-0295, "The Air Force Flight Test Center Artificial Icing and Rain Testing Capability Upgrade Program".

Spray Cloud Calibration and System Improvements

Calibration of the upgraded dual-use tanker spray cloud using both the circular and square arrays was performed in 1988. The square array produced an acceptable cloud but was not used because of its heavy weight and ice buildup problems. Both arrays used ¼ J air atomizing nozzles manufactured by Spraying Systems Co. The calibration data using the circular array showed that the cloud median volumetric diameter (MVD) and liquid water contents (LWC) were reasonably within 14 CFR Part 25, Appendix C conditions, but improvement was still needed. This array was rebuilt in 1991 to eliminate internal leakage, which had caused unacceptable ice accumulation around the nozzles. In addition, the bleed air system was upgraded, which included improved boom seals to allow higher air pressure and temperature. Operational check flights conducted from March through June 1992 showed vastly improved boom handling due to the elimination of binding and stowage problems. The upgraded bleed air system increased the mass flow and temperature provided to the array, along with improved control from the operator's console. Longer test flights and improved cold weather operations were then possible.

Cloud calibrations were again conducted in July 1992 using an instrumented Gates 36 Learjet. The instrumentation consisted of two laser spectrometers, a Johnson and Williams LWC probe, and indicators for ambient air temperature, dew point, and airspeed. A summary of the calibration data is shown in table 1.

TABLE 1. ICING CALIBRATION DATA SUMMARY

Altitude (1000 ft)	True Airspeed (kts)	Relative Humidity (%)	Median Volumetric Diameter (μm)[1]	Liquid Water Content (g/m^3)
19.2	229	44	18	0.191
19.3	228	45	19	0.244
19.2	228	44	21	0.336
19.2	229	45	24	0.399
17.6	214	37	23	0.464
17.5	203	69	23	0.502
17.5	206	61	23	0.614
17.5	205	59	24	0.818
17.5	223	27	40	0.929
17.4	208	39	39	1.161
17.4	205	67	51	1.382
17.4	206	53	67	1.574
17.4	207	53	78	2.164

1. μm = micron ($meter^{-6}$)

Comparison of the artificial conditions provided by the tanker spray system to 14 CFR Part 25, Appendix C conditions as measured during the 1988 and 1992 calibrations is shown in figures 1 and 2. Both the 1988 and 1992 calibration data in figures 1 and 2 show that the tanker was capable of generating an artificial icing cloud which is within the criteria of Appendix C. In addition, the 1992 data show a shift towards the left, which indicates that the tanker cloud characteristics more closely matched Appendix C envelopes. However, the data in figure 2 indicates that more research needs to be done with the water spray system to improve the cloud characteristics, if the goal is to attain and stay within Appendix C envelopes, particularly at the higher LWC.

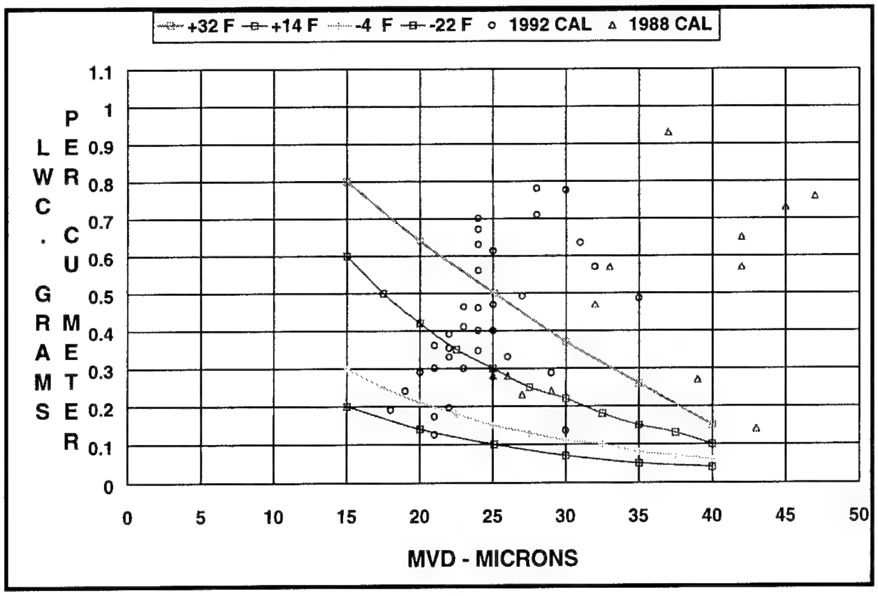


FIGURE 1. CONTINUOUS MAXIMUM (STRATIFORM CLOUDS) (14 CFR Part 25, Appendix C vs spray cloud conditions, LWC vs MVD)

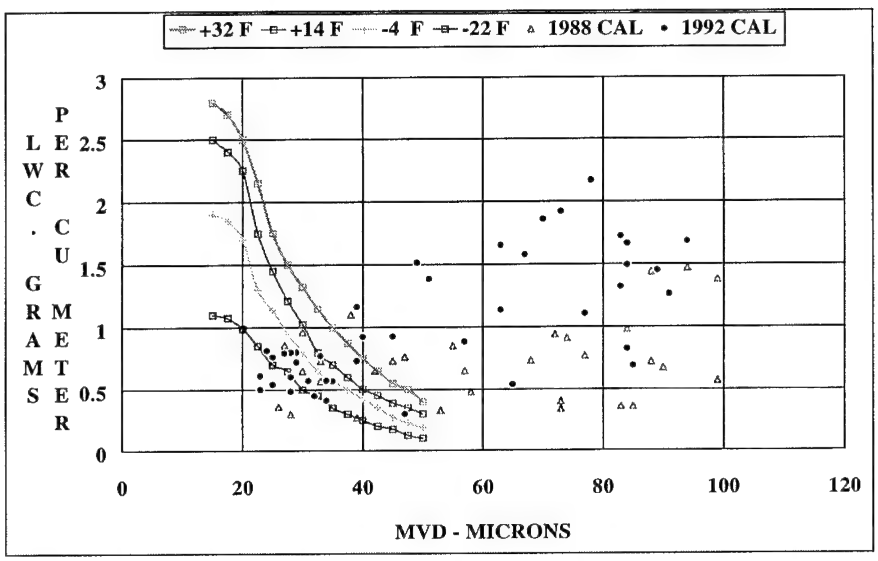


FIGURE 2. INTERMITTENT MAXIMUM (CUMULIFORM CLOUDS) (14 CFR Part 25, Appendix C vs spray cloud conditions, LWC vs MVD)

The liquid water content versus separation distance between the test aircraft and the tanker spray array is shown in figure 3. These calibration data were taken with an outside relative humidity (RH) of 27 percent.

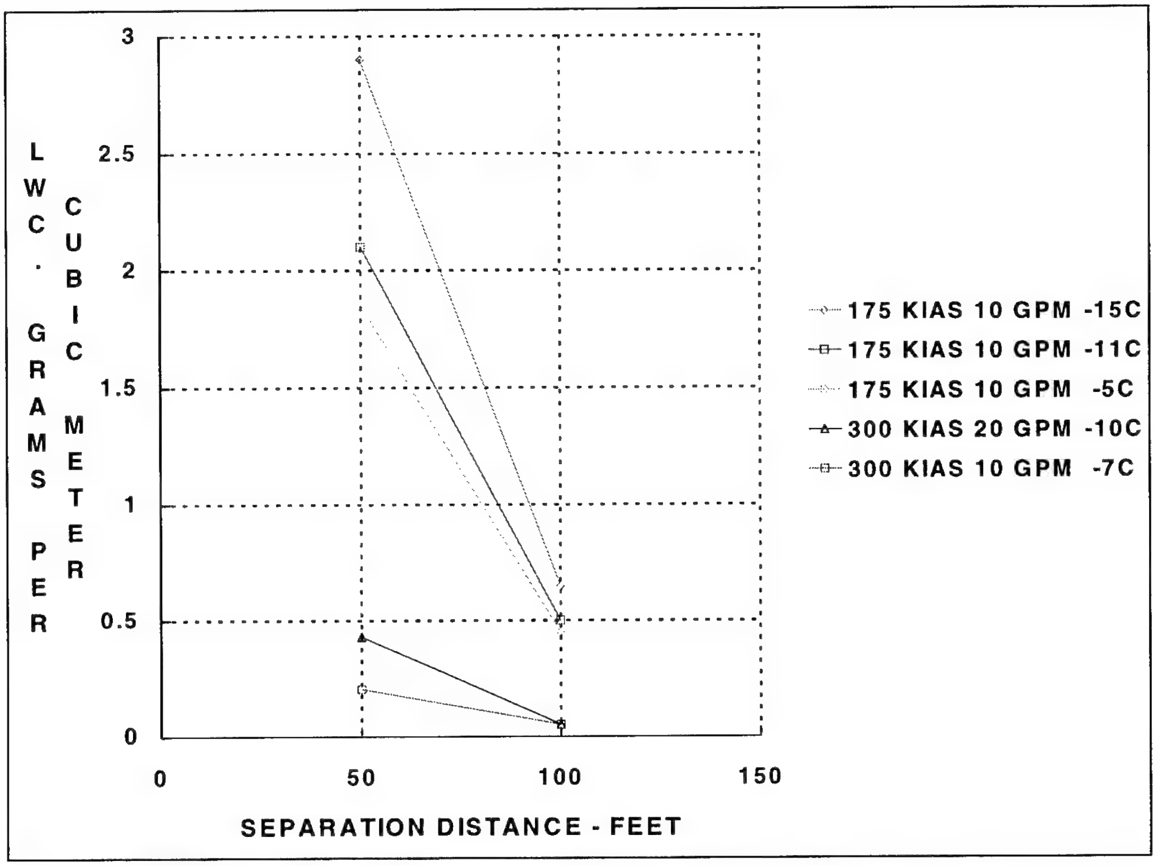


FIGURE 3. SPRAY CLOUD VS SEPARATION DISTANCE
(distance from array, 27% RH)

The cloud shape generated by the spray array was obtained by using the calibration sweep data. The horizontal sweep data indicated a relatively homogeneous cloud near its center but decreasing in LWC towards the sides. Because of the limited number of horizontal sweeps conducted, the MVD distribution could not be accurately determined and is not shown. The vertical sweep data indicated a maximum LWC and MVD just below the cloud center due to gravitational effects, as shown in figure 4. Previous tanker calibration data indicated the bottom of the cloud was 25 percent higher than the top in water concentration. Figure 4 shows the bottom of the cloud was 6 percent higher than the top in water concentration. This improvement was a result of the water spray and boom improvements made during the upgrade.

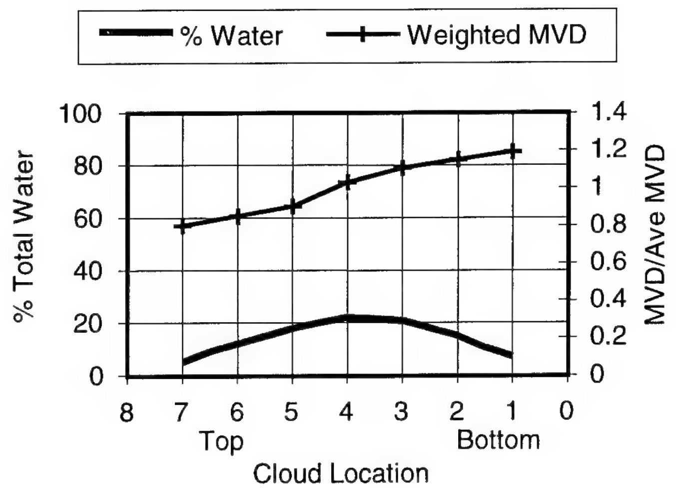


FIGURE 4. VERTICAL CLOUD PROFILE

Through the use of photographs taken during the calibration, the visible cloud size was measured by comparing to the known size of the Learjet calibration aircraft. The cloud diameter varied from 4.0 feet to slightly over 8 feet, depending on separation distance.

Cloud Distribution Comparison to Natural Conditions

At the request of the Federal Aviation Administration (FAA), an artificial icing evaluation of the ATR-72 commuter aircraft was conducted in December 1994. The objective was to produce supercooled drizzle drops (SCDD), which were suspected of contributing to the ATR-72 crash near Roselawn, Indiana, on 31 October 1994. A low percentage of natural icing clouds contain these large droplets, which are typically outside the 14 CFR Part 25, Appendix C icing envelopes. Changes in the nozzle arrangement and variation of water and bleed air parameters were made in an effort to produce them.

Calibration of the spray cloud at several atmospheric conditions at approximately 19,000 feet PA in the Edwards AFB airspace was then conducted by Dr. Ray Hobbs of Aeromet, Inc. using an instrumented Learjet with particle measuring probes (PMP). One criterion of the test was to keep the ambient air temperature within ±1°C. This proved somewhat difficult to maintain with the tanker, particularly at 10,000 feet or lower, because of the transition between flat desert and mountainous terrain in R2508 (Edwards local airspace), which can cause significant variations in ambient air temperature at a given flight level. Air Force test requirements are not so stringent, allowing the tanker to maintain only 2 or 3 degrees within the desired ambient temperature.

The Aeromet calibration data showed that the tanker spray system could produce a cloud distribution containing large drops. Maximum calculated MVDs were in the range of 120 μm vs a desired range of up to 200 μm; however, this was sufficient to identify the icing problems with the ATR-72. The PMP instrumentation used by Aeromet on the Learjet consisted of industry-standard sensors for measuring droplet size, and LWC was measured with a hot wire bridge type instrument. A Forward Scattering Spectrometer

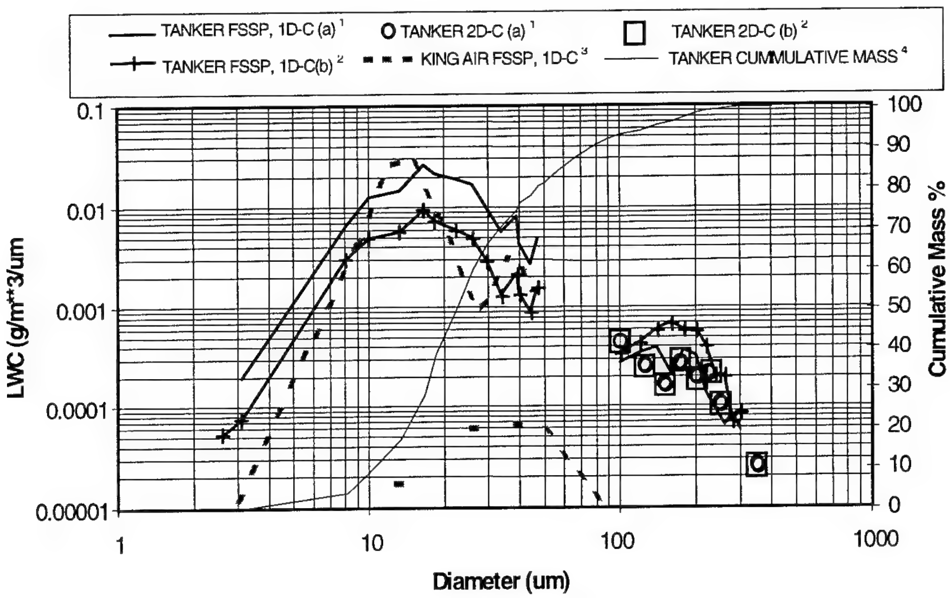
Probe (FSSP), a one-dimensional probe (1D-C), and a two-dimensional probe (2D-C) measured droplet size in the following ranges.

a. FSSP (3 to 45 μm)
b. 1D-C (20 to 300 μm)
c. 2D-C (25 to 800 μm)

In a 1996 technical paper co-authored by former Edwards AFB icing engineer Dr. Russell A. Ashenden and Dr. John D. Marwitz of the University of Wyoming (reference 1), a comparison was made of the USAF tanker icing cloud SCDD distributions and natural icing cloud SCDD distributions. The USAF tanker icing cloud was calibrated by Aeromet in 1994. The natural cloud distribution data were obtained through atmospheric research using the instrumented Wyoming King Air A200T in areas where SCDD conditions were encountered. The King Air instrumentation was similar to that of the Aeromet Learjet.

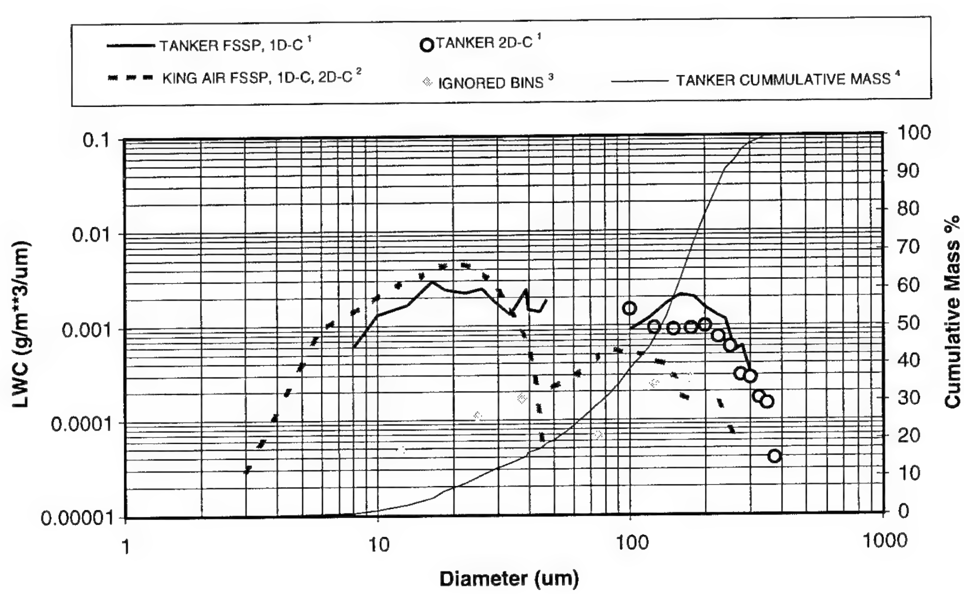
Measured water spray tanker cloud and natural icing cloud distributions (King Air) are shown in figures 5 through 8. Figures 5 and 6 show natural distributions that fall within the 14 CFR Part 25, Appendix C envelopes (see figures 1 and 2). Figures 7 and 8 show natural distributions that fall outside these envelopes. Figure 8 shows the comparison without FSSP data; therefore focusing on the drizzle regime (i.e., droplets ranging in volumetric diameter from 40 to 300 μm). Figure 6 shows a natural drizzle distribution outside Appendix C envelopes when using 80 percent volumetric diameter (80VD) in the calculation; however, the calculated MVD using 50 percent volumetric diameter (50VD) places this natural condition within the Appendix C envelopes. The 80 percent volumetric diameter (80VD) has been proposed for the natural drizzle environments to define the larger droplet sizes. This parameter has 80 percent of the water volume in droplets smaller than 80VD and 20 percent in droplets larger than 80VD. The 80VD parameter is more representative of the large droplets in the total droplet distribution.

The data from figures 5 through 7 indicate a bimodal characteristic of the distribution for both the tanker and natural condition (though not as pronounced for the tanker). Both modes show a favorable comparison of the artificial distributions produced by the tanker to those measured in the natural environment by the King Air instrumentation. As mentioned before, however, the tanker data were gathered at only the one altitude (approximately 19,000 feet). Therefore, it is unknown if the aircraft bleed air system could produce, for example, the temperatures and flow necessary to create large droplet MVDs with desired LWCs at higher altitudes. Some suppression of the 20 μm mode in the tanker distributions also occurred, probably because of evaporation. The tanker calibrations were conducted over Edwards AFB in the high desert of California, where the relative humidity is normally very low.



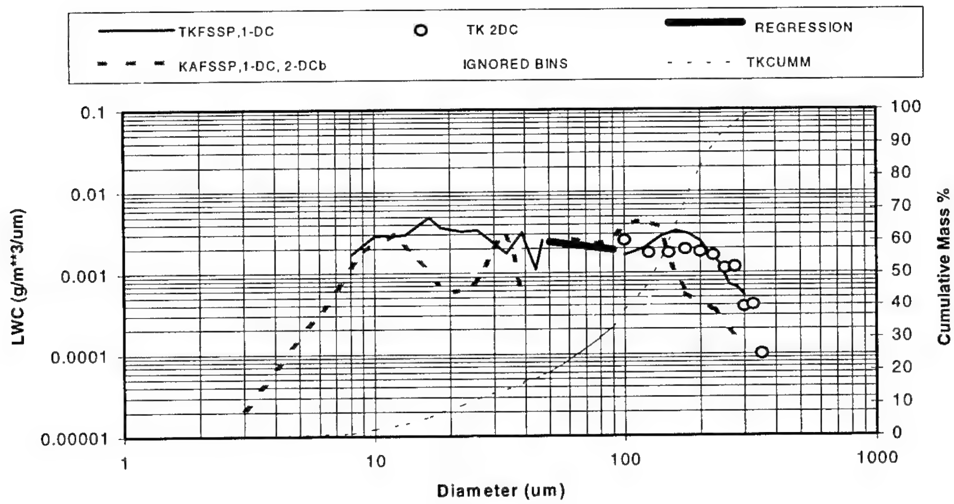
Notes:
1. Tanker distribution (a) obtained 12/19/94 at 234616 UTC - LWC: 0.61g/m³, MVD: 22 µm; 80VD: 47 µm
2. Tanker distribution (b) obtained 12/19/94 at 234719 UTC - LWC: 0.29 g/m³, MVD: 38 µm; 80VD: 140 µm
3. Natural distribution (King Air) on 3/7/94 at 225344 UTC - LWC: 0.28 g/m³, MVD: 17 µm; 80VD: 23 µm
4. Thin-dotted line indicates the cumulative mass for tanker distribution (a)

FIGURE 5. TANKER AND NATURAL DISTRIBUTIONS FOR 14 CFR PART 25, APPENDIX C CONDITIONS



Notes:
1. Tanker distribution obtained 12/18/94 at 190609 UTC - LWC: 0.41 g/m³, MVD: 140 µm; 80VD: 200 µm
2. Natural distribution (King Air) measured 3/7/94 at 241440 UTC - LWC: 0.15 g/m³, MVD: 31 µm; 80VD: 122.2 µm
3. First 3 and 4 bins of 1D-C and 2D-C samples, respectively, were ignored in the statistics (undersampling)
4. Thin-dotted line indicates cumulative mass for tanker distribution

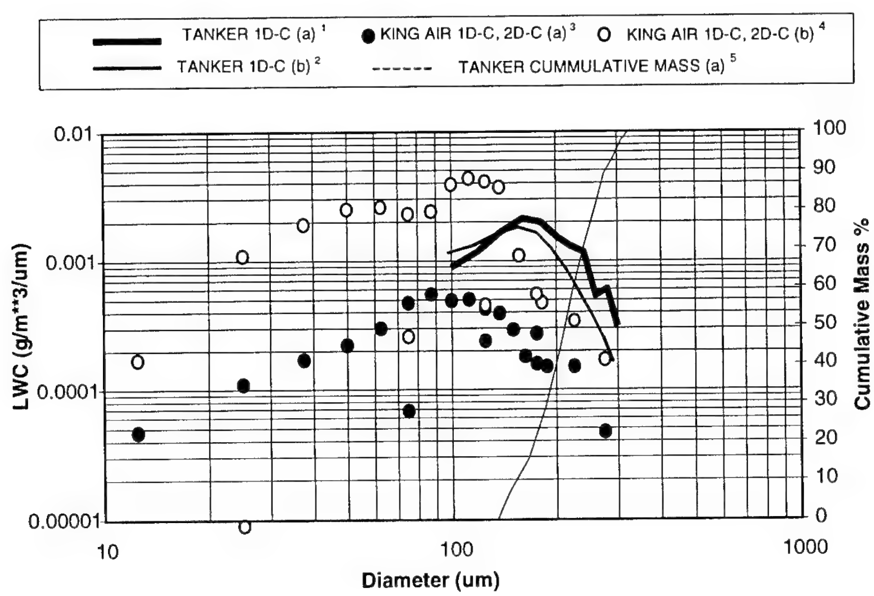
FIGURE 6. TANKER AND NATURAL SCDD DISTRIBUTIONS WITHIN 14 CFR PART 25, APPENDIX C CURVES



Notes:

1. Tanker distribution obtained 12/19/94 at 174039 UTC - LWC: 0.61 g/m³, MVD: 140 µm; 80VD: 195 µm
2. Natural distribution (King Air) obtained 1/18/83 at 242358 UTC - LWC: 0.44 g/m³, MVD: 112 µm; 80VD: 146.7 µm
3. First 3 and 4 bins of 1D-C and 2D-C samples, respectively, were ignored in the statistics (undersampling)
4. Thin-dotted line indicates the cumulative mass for the tanker distribution

FIGURE 7. MASS-WEIGHTED TANKER AND NATURAL SCDD DISTRIBUTIONSOUTSIDE OF 14 CFR PART 25, APPENDIX C CURVES



Notes:

1. Tanker distribution (a) obtained 12/18/04 at 190609 UTC with 1D-C LWC: 0.27 g/m³, MVD: 180 µm, and 80VD: 219 µm
2. Tanker distribution (b) obtained 12/16/94 at 190609 UTC with 1D-C LWC: 0.24 g/m³, MVD: 160 µm, and 80VD: 200 µm
3. Natural (King Air) Distribution (a) obtained 3/7/94 at 241440 UTC with 1D-C and 2D-C LWC: 0.06 g/m³, MVD: 123 µm, and 80VD: 183 µm
4. King Air Distribution (b) obtained 1/18/83 at 242358 UTC with 1D-C and 2D-C LWC: 0.39 g/m³, MVD: 118 µm, and 80VD: 151 µm
5. Thin-dotted line indicates cumulative mass for tanker distribution (a)

FIGURE 8. TANKER AND NATURAL SCDD DISTRIBUTIONS WITHOUT FSSP DATA

KC-135R MULTI USE TANKER

Description

No USAF water spray tanker is available at the present time. However, a DoD Central Test and Evaluation Investment Program has been established to replace the old tanker water spray system with a newer and more capable system. Called the "Airborne Icing Tanker" (AIT), this new capability will be installed on a KC-135R, and should provide a larger cloud and droplet MVD within the 14 CFR Part 25, Appendix C envelope up to 1.0 g/m^3. The KC-135R tanker will contain multiuse provisions to reduce operating costs. The current plan is to use the existing spray boom that has a new octagonal spray array with more than 200 nozzles that can produce a larger diameter icing cloud. The development effort includes participation by the U.S. Navy and U.S. Army. The goal is to have the AIT ready in late CY2001 or early CY2002 to meet the F-22 schedule for in-flight icing tests. Navy technology in spray arrays and nozzles has been investigated, and the Navy-designed octagonal array will be used in F-22 tests. The new capability is vital to the safe testing of future new military aircraft and could significantly reduce flight time spent on natural icing and shape tests of civilian aircraft.

Strengths

- **Year-round availability of icing conditions.** Airspeed ranges from 150 to 300 KIAS are possible, and tests can be conducted from 5,000 to 30,000 feet PA. Using both tanker outside air temperature (OAT) production and test OAT instrumentation measurements, the tanker can be flown at altitude to specific temperatures required for the type of ice desired. Temperatures above freezing up to altitudes of 10,000 feet mean sea level (MSL) occur most of the time in the high desert at Edwards AFB, which allows ice shedding characteristics to be evaluated after selected test points.

- **Continuous cloud.** Continuous rate of accretion allows real time observation and documentation of ice shape buildup. Water capacity of 2000 gallons allows testing up to 2 1/2 hours.

- **Selected areas of exposure using the four- to slightly-over eight-foot diameter spray cloud.** Critical areas on new aircraft can be evaluated without the safety risks associated with exposure of the entire vehicle. With the improved control of the spray boom, the artificial cloud can be accurately placed on selected areas by the boomer with minimum effort on the part of the test aircraft pilot.

- **Accurate positioning of the behind the tanker.** A LDMS is used to accurately measure the distance from the tanker spray array to either the calibration aircraft or the selected area of the system under test.

- **Good documentation of ice accretion possible.** A video camera in the LDMS pod can be used to document ice accretion very well when sea marker dye is used in the spray water. Chase aircraft video documentation is possible in the clear-air visibility conditions existing most of the time at Edwards AFB. Ice depth gauges can be placed on exposed surfaces for documenting ice accretion rate and for safety of test when test points are limited to specific ice thickness during buildup in test conditions. Atmospheric data is available through the use of Rawinsonde recording (local

weather balloons) and from the tanker instrumentation, which includes relative humidity measurement.

- **Greater Coverage of 14 CFR Part 25, Appendix C Criteria.** MVDs in the range of 20 to 40 μm at LWCs below approximately 1 g/m^3 will be produced by the upgraded spray system using the new octagonal icing array.
- **SLD Icing Conditions Readily Available.** The tanker spray system can generate artificial icing clouds with LWCs and MVDs within the 14 CFR Part 25, Appendix C envelopes, except for the higher LWCs specified for intermittent maximum conditions. The artificial icing cloud distributions produced by the tanker show favorable comparison to the natural conditions measured in the natural environment for both 14 CFR Part 25, Appendix C envelopes and the SCDD range.
- **Models not required.**
- **Safety.** Can fly into visual meteorological conditions (VMC) immediately.
- **Testing can be accomplished in any weather.**
- **Full size Reynolds Number.** Full-scale flight Reynolds number as opposed to scaled-down numbers of models provides more accuracy in test results.
- **Time saved by not having to look for natural icing conditions is very large.**
- **Reasonable test costs compared to the previous AF tanker cost** (if icing capability is re-established on the multiuse tanker). Multiuse of the new tanker for noninstrumented air refueling and as a mod platform for AFSC should reduce the cost per flight hour by about one-half.

Limitations

- **Full Coverage of 14 CFR Part 25, Appendix C Criteria.** Even though the data was shifted to the left after system upgrades and more closely matched the FAA specified conditions, more research needs to be done with the new USAF tanker water spray system to improve cloud characteristics, particularly at the higher LWCs for the intermittent maximum conditions. Only partial coverage of conditions in the envelopes is possible.
- **Difficult to Simulate Large Drops (Freezing Drizzle (ZL), Freezing Rain (ZR)).** During ATR-72 tests, the maximum calculated MVDs were in the range of 120 μm. More research needs to be done with array variants and different types of nozzles to improve the supercooled large droplets (SLD) range of the artificial icing cloud.
- **Small cloud diameter.** Small cloud diameter of 4 to 8 feet does not allow complete coverage of large areas such as Boeing 777 type turbofan engines.
- **Cloud Uniformity.** Fairly homogenous cloud after tanker upgrades in 1988 and 1992 with about 6 percent more water near the bottom than the top. However, LWC decreases toward the outer edges.
- **Tests in natural conditions still required.** Qualification of Air Force and other government aircraft for flight in icing conditions does not require FAA certification.

In this case, tests in natural icing are desired but not mandatory. However, when the Air Force tanker is used to support commercial programs for FAA certification, tests in natural icing conditions are required.

Uncertainties

- **Effect of humidity.** Evaporation of small droplets occurs in the low relative humidity in the California high desert. This problem increases in magnitude with increase in test vehicle separation distance.

- **Temperature control.** With OAT data available from both special instrumentation and the tanker production gage, the aircraft could be flown to within 2 or 3 degrees of the desired temperature at altitude. However, for special applications such as duplicating the ATR-72 scenario, the desired range of ±1 degree or less was difficult to maintain.

- **Effect of drop velocities.** Drops may have higher horizontal velocity components than natural drops. The drops are ejected from the array nozzles at the speed of the tanker. JTD Environmental Services has shown that the horizontal component is nearly zero at 50 feet behind the array. If closer than 50 feet, the ice accretion characteristics may be slightly different than for natural conditions.

- **Effect of turbulence.** Turbulence from tanker can affect the accretion pattern on test aircraft. However, the maneuverable boom on the USAF tanker allows boom operators to place the spray array below the turbulent area caused by the engine exhaust, which greatly reduces the effects of turbulence on the test aircraft.

- **Effect of drop temperature.** How long or what separation distance is required to assure that the drops are supercooled.

- **Availability of tanker.** Full operational capability of the AIT is scheduled for the third quarter of FY02.

- **High cost of USAF tanker.** If multiuse capability of the new USAF tanker does not generate sufficient utilization rate, cost of operation will turn business away and force customers to look for other options. Requirement for cloud calibration during some tests could further increase costs.

CESSNA ICING TANKER

Description

The Cessna icing tanker is a modified T-47, with enough water for about 40 minutes of "water on" air work. The aircraft runs a water pressure of 120 psi inside the cabin. The spray boom is a "V" shape extension off the top of the aircraft vertical fin, and generates a spray plume about 4 to 6 feet in diameter, depending on separation distance. The array contains four hydraulic atomization type nozzles, which produce small droplet sizes by injecting the water at opposing angles into the airstream. The Air Force tanker used nozzles that injected air parallel to and surrounding the water jet, which were both injected directly aft into the airstream. The Cessna nozzles have been calibrated twice, and both calibration reports are available by request of Cessna.

Through the above mentioned reports and data collected during many years of use, it has been determined that the Cessna system provides a droplet diameter of 30 µm. The required LWC is found by using the plots in Appendix C of 14 CFR Part 25. This is an extremely conservative approach but has worked well in the past. The spray boom is partially heated, but will ice up if the nozzles are dirty (i.e., the water doesn't leave the spray nozzle in a clean manner). Also, all conditions that are not optimum result in droplets that are larger than 30 µm (conservative). LWC for the test conditions is measured using instrumentation aboard the test aircraft, and can be varied by changing distance from the tanker.

Strengths

- **Year-round availability of icing conditions.**
- **Icing work can be accomplished in any weather.**
- **Continuous cloud.**
- **Selected areas of exposure.**
- **Full size flight Reynolds Number.**
- **Results are conservative.**
- **Tanker results can be used to design actual ice shapes for further testing.**
- **Time saved not having to look for ice in natural environment is very large.**

Limitations

- **Results sometimes very conservative.** The tanker provides partial coverage of 14 CFR Part 25, Appendix C criteria. It is possible to achieve a 30 µm droplet size but only for low LWC, because there are only four nozzles on the spray array.
- **Tests in natural icing still required.**
- **Small cloud diameter.**
- **Spray array not maneuverable.** Unlike the AF tanker icing array, which can be maneuvered and kept in the desired position, the fixed position of the nozzles on all other tankers makes it more difficult for the pilot to keep the system under test in the array plume.
- **Tanker (and crew) expensive to operate.** Any requirement for cloud calibration during tests will further increase costs.
- **Limited test time.**
- **Tests in natural icing conditions still required.**

Uncertainties

- **Effect of humidity.**
- **Temperature control.**

- **Effect of drop velocities.**
- **Effect of drop temperature.**
- **Cloud uniformity.** No information is available on drop size distribution and LWC concentration.
- **Effect of turbulence.** Turbulence from the tanker can affect accretion pattern on test aircraft.

RAYTHEON ICING TANKER

Description

The Raytheon icing tanker is a type-B200 King Air twin-engine turboprop, high T-tail aircraft. The normal tanker speed and altitudes for testing are 160 kts and 5,000 to 18,000 ft. The aircraft is single pilot but normally flown with two pilots, and requires a water tank operator. The water tank is locally manufactured, removable, and holds approximately 300 gallons. It feeds bleed air aspirated icing nozzles based on bleed air pressure to the tank. There are four nozzles in the top of the vertical tail to provide the icing pattern. The plume is approximately 4 feet in diameter at approximately 100 feet behind the tanker. Raytheon currently has four nozzle sizes available: 0.066, 0.094, 0.133, and 0.188 inch in diameter that produce the range of LWC and droplet size shown in table 2. The previous Air Force tanker had 100 nozzle positions, 49 of which were actually used for spraying water and the rest used for bleed air heating to help keep the nozzles from icing up. The new Air Force tanker icing array will have 216 nozzles. The U.S. Army HISS contains eight nozzles, the Cessna tanker contains three nozzles, and the Dornier spray array will accommodate up to 61 nozzles.

TABLE 2. RAYTHEON NOZZLES

Nozzle Size (in)	Average LWC (g/m^3)	Average Drop Size (μm)
0.066	0.04	111
0.094	0.10	87
0.133	0.20	97
0.188	0.35	131
baseline tube	0.77	150

Control is somewhat crude with no precise regulation of flow or monitor of output. The installation was flown with the JTD particle measurement system (PMS) to calibrate it. Output data is available on request, but is not a guarantee of specific performance.

Strengths

- **Icing tests can be accomplished in any weather.**
- **Year-round availability of icing conditions.**
- **Continuous cloud.**

- **Selected areas of exposure.**
- **Availability of tanker.** Raytheon can provide the B200 aircraft, flight crews, maintenance, photo coverage, and limited instrumentation to customers on a subcontract basis. Point of contact is Max Mills at Raytheon (e-mail Max_Mills@raytheon.com), telephone (316) 676-5481.
- **Full size Reynolds Number.**

Limitations

- **Small cloud diameter.**
- **Spray plume not maneuverable.**
- **Limited test time.**
- **Tests in natural icing conditions still required**
- Simulation of SLD conditions may be possible using the baseline tube. However, without precise regulation of flow, accuracy in simulation of a natural SLD condition is unknown.
- **Only some criteria in 14 CFR Part 25, Appendix C envelopes can be met.**

Uncertainties

- **Effect of humidity.**
- **Temperature control.**
- **Effect of drop velocities.**
- **Effect of drop temperature.**
- **Cloud uniformity.**
- **Effect of turbulence.** Turbulence from the tanker can affect accretion pattern on test aircraft.

U.S. ARMY ICING SPRAY SYSTEM

Description

The U.S. Army HISS consists of a horizontal spray boom arrangement mounted on the rear of a CH-47 Chinook helicopter. The cloud size is 8 feet high by 36 feet wide, which is designed to expose the entire length of the rotor blades of a helicopter under test to the plume. Spray nozzles are hydraulically aspirated. Water is contained in a tank within the fuselage. The test airspeed range is from 80 to 130 KIAS and the test altitude range is from 1,500 ft AGL to 12,000 ft MSL. Test temperature range is down to -23.5° C. Below that temperature the nozzles begin freezing up. Tests are conducted during the winter months each year at Duluth, Minnesota.

Strengths

- **Large spray plume.**
- **Full size Reynolds Number.**
- **Continuous cloud.**
- **Good documentation of results.** During winter months in Duluth, ice will not melt, and test vehicles can land with ice shapes still intact for observation and documentation.

Limitations

- **Partial coverage of 14 CFR Part 25, Appendix C criteria.** At higher water flow rates (higher LWC), MVD exceeds the 14 CFR Part 25, Appendix C envelopes. Also at low relative humidity and moderate flow rates, MVD may exceed the Appendix C envelope. Therefore, the size of droplets produced is subject to evaporation effects.
- **Simulation of SLD conditions may not be possible.**
- **Spray cloud shape and size.** May not be suitable for applications other than helicopter blade icing. Some helicopter rotors are larger in diameter than the width of the spray cloud, so the test helicopter array must be moved back and forth across the cloud to expose all surfaces of the rotor blades.
- **Cloud distribution.** The water droplet size distribution of the cloud contains a higher concentration of large drops than is normally found in naturally occurring clouds.
- **Ice Shapes.** Shapes of ice formed are not as varied as observed after natural encounters.
- **Spray boom not maneuverable.**
- **Tests in natural icing still required.** (Only if HISS is used to support commercial programs.)

Uncertainties

- **Effect of humidity.**
- **Temperature control.**
- **Effect of drop velocities.**
- **Effect of drop temperature.**
- **Cloud uniformity.**
- **Effect of turbulence.** Turbulence from tanker can affect accretion pattern on test aircraft.
- **Availability of tanker.** Tanker is only available during winter months, when altitudes for desired icing conditions (ambient temperatures) are low enough for tanker to reach and maintain.

Dornier Icing Tanker

Description

The Dornier icing tanker used for certification flights is a DO228-200, D-ICDO. It is equipped with two water tanks of 500 liters each. The system provides a spray time of about 37 minutes with 43 nozzles and about 26 minutes with 61 nozzles in the spraybar. The pressure of the water pump is 70 bar (adjusted). To avoid freezing of the nozzles, it is necessary to have noninterrupted water flow in the nozzles. This works until -25°C. For cloud calibration and certification flights, L212.205 nozzles (from Lechler GmbH, Metzingen, Germany) are used in the spraybar. The outlet diameter of the nozzles is 0.6 mm and the narrowest cross section is 0.3 mm. The calculated mass flow for 70 bar with 61 nozzles is 38.4 l/min and for 70 bar with 43 nozzles is 27.1 l/min. During the calibration the relative humidity in percent and the rate of water flow in liters per minute is measured and recorded. A digital global positioning system (DGPS) is used for accurate position between the tanker aircraft and the test aircraft (in three dimensions). A reference global positioning system (GPS) is installed in the tanker aircraft. With this configuration an accuracy of measurement of 30 cm is possible. The tanker aircraft is also equipped with two video cameras above and below the spraying rig in order to position the test aircraft accurately in the water spray plume. During a recent certification test, a LWC between 0.3 g/m^3 and 1.6 g/m^3 (depending on distance between tanker and test aircraft, number of nozzles and outside air temperature) with an MVD of about 40 microns was achieved.

Strengths

- **Year-round availability of icing conditions.**
- **Icing work can be accomplished in any weather.**
- **Continuous cloud.**
- **Selected areas of exposure.**
- **Full size flight Reynolds Number.**
- **Time saved not having to look for ice in natural environment is very large.**
- **Accurate space position measurements of the tanker and system under test.**

Limitations

- **Tests in natural icing still required.**
- **Spray array not maneuverable**. Unlike the AF tanker icing array, which can be maneuvered and kept in the desired position during test, the fixed position of the nozzles on all other tankers makes it more difficult for the pilot to keep the system under test in the array plume.
- **Limited test time.**

Uncertainties

- **Effect of humidity.**

- **Temperature control.**
- **Effect of drop velocities.**
- **Effect of drop temperature.**
- **Effect of turbulence.** Turbulence from tanker can affect accretion pattern on test aircraft.
- **Cloud uniformity.** No information is available on drop size distribution and LWC concentration.

SUMMARY OF TANKER ATTRIBUTES

Strengths of icing tankers are similar, except for the Army HISS. They generally provide year-round capability to accomplish testing in any weather and offer full-size Reynolds numbers. They provide selected areas of icing exposure and the clouds are continuous. The USAF tanker, if re-established with the same (or improved) capability as that which previously existed, will also provide good documentation of ice accretion, SLD icing conditions, and safety of flight enhancement.

Limitations of icing tankers are also similar in that they only partially meet (or do not meet) the criteria of 14 CFR Part 25, Appendix C, may not be able to provide SLD simulation (except for the USAF tanker), and produce small cloud diameters. All still require tests in natural icing conditions for FAA certification. A few exceptions to this requirement are known. Among these were the General Electric (GE) injector test conducted at Edwards AFB several years ago that did not require natural testing, and the Boeing 777 engines that were partially qualified using the USAF tanker without requiring natural icing testing.

Uncertainties of icing tanker capability are the same in that the effects are either unknown or only partially known in areas of humidity, temperature control, drop velocities, and drop temperature (distance behind array where drops become supercooled). Additional uncertainties of the USAF tanker are the future availability of the new multiuse KC-135R, and its cost of operation.

REFERENCES

1. A Comparison of the Air Force Water Spray Tanker Artificial Drizzle Cloud Distributions to the Natural Environment, AIAA-96-0632, Ashenden, Russell A. and Marwitz, John D., 15 January 1996.

LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS

Abbreviation	Definition	Unit
μm	micron (meter $^{-6}$)	---
1D-C	One-dimensional Cloud Optical Array Probe	---
2D-C	Two-dimensional Cloud Optical Array Probe	---
14 CFR	Title 14, Code of Federal Regulations	---
AGL	above ground level	---
AIT	Airborne Icing Tanker	---
C	centigrade	---
DGPS	digital global positioning system	---
DoD	Department of Defense	---
FAA	Federal Aviation Administration	---
FAR	Federal Aviation Regulations	---
FSSP	Forward Scattering Spectrometer Probe	---
g/m^3	grams per square meter	---
GPS	global positioning system	---
HISS	helicopter in-flight icing system	---
KIAS	knots indicated airspeed	---
KIAS	knots indicated airspeed	---
LDMS	laser distance measuring system	---
LWC	liquid water content	---
MSL	mean sea level (altitude)	---
MVD	median volumetric diameter	---
OAT	outside air temperature	---
PA	pressure altitude	---
PMP	Particle Measuring Probe	---
RH	relative humidity	---
SCDD	supercooled drizzle droplet	---
SLD	supercooled large droplet	---
USAF	United States Air Force	---
UTC	Universal Time Code	hrs:min:sec
VMC	visual meteorological conditions	---
VD	volumetric diameter	---
50VD	50 percent volumetric diameter	---
80VD	80 percent volumetric diameter	---

CAPABILITIES AND LIMITATIONS OF ICING SIMULATORS IN THE SIMULATION OF ICING CONDITIONS FOR THE DESIGN AND CERTIFICATION OF AIRCRAFT AND ENGINES

Environmental Chambers

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Wayne Drake, McKinley Climatic Laboratory, Eglin Air Force Base

SIMULATION REQUIREMENTS AND CURRENT CAPABILITIES

The Federal Aviation Administration (FAA) currently requires manufacturers of aircraft and aircraft propulsion engines to satisfy specific regulations intended to ensure that this type of equipment can successfully operate in specified icing conditions. The typical scenario for meeting these requirements involves the use of computer codes to estimate the types of ice buildup likely to occur on specific designs. This computer work then may evolve into the generation of artificial ice shapes to be mounted on the aircraft for wind tunnel and/or flight test evaluations. The effort may also extend into the use of icing tunnels and/or in-flight tanker icing evaluations. All of these methods are useful and valuable tools for evaluating the ability of the aircraft or engine to operate in an icing environment. Each method has its own advantages. The FAA still requires that the equipment be evaluated while flying in an actual icing condition.

Another method of evaluation currently available is the use of environmental chambers. A search was conducted to determine the current simulation capabilities of the largest known environmental chambers within the United States. Although many commercial companies own and operate environmental chambers, the largest of these environmental chambers are typically owned and operated by the Department of Defense (DoD) presumably because of the high cost of construction of such a facility. Many DoD and commercial facilities were contacted to determine their capability to produce any type of icing condition whatsoever. It should be noted that this review was not all-encompassing and there may, in fact, be additional environmental chambers (most likely within the automotive industry) which could provide the necessary conditions to conduct icing evaluations for large equipment. Here, large is defined as being at least large enough to accommodate equipment the size of an aircraft jet engine, complete with nacelle and deicing/anti-icing equipment.

There appears to be an extremely high number of small environmental chambers that conduct low-temperature evaluations but have no icing capability. These chambers are usually only a few cubic feet in volume and offer very little capability with respect to aircraft deicing/anti-icing equipment.

However, seven large environmental chambers were found which may offer, at some level, simulations of several icing conditions which might be useful and valuable to the airplane, rotorcraft, and engine manufacturers. Of the seven large environmental chambers found, all conduct evaluations of freezing rain and also attempt to generate artificial snow. Of these facilities, about half must resort to using prechill tanks for water supply and employ the use of hand wands for spray application. This is necessary

because most environmental chambers do not possess the refrigeration capacity to compensate for the large energy change required to remove the latent heat from the water source on a real-time basis (i.e., a tremendous amount of energy is required for change of state from water to ice).

The other large environmental chambers employ spray arrays mounted in the ceiling of the facility or have portable spray frames. About half of the large chambers employ wind machines (varying up to about 50 mph) and all take manual measurements of ice/snow depth, density, and other characteristics.

The primary impetus for this review is to identify potential capabilities specifically for the evaluation of the ability of an aircraft or aircraft propulsion engine to operate in an icing environment. Recently, and as a result of discussions generated in support of this section of the report, the definition of this environment has been somewhat expanded from the Appendix C of 14 Code of Federal Regulations (CFR), Part 25 to a more generic one encompassing other types of icing conditions. For example, the engine manufacturers have expressed interest in conducting evaluations involving ingestion of ice crystals. Additionally, several other manufacturers have expressed interest in evaluations involving freezing rain and ground fog icing.

All but one of the large environmental chambers must be excluded if the intent is to conduct evaluations of full-scale aircraft. Additionally, all but this chamber must be excluded if the user requires operation of the engine while under condition.

The McKinley Climatic Laboratory is the largest environmental chamber in the entire world. The facility generates freezing rain, snow, and other icing conditions. It is large enough to accommodate full-scale aircraft (up to a Boeing 747). It is the only environmental chamber found which provides conditioned Air Makeup to allow operation of jet engines at the required test conditions. While a jet engine is operated inside the facility, the engine engulfs a very large volume of conditioned chamber air and expels this air as exhaust. The facility places large ducts immediately aft of the jet engine to create a channel through which the exhaust may be removed from the chamber. All of the conditioned air which passes through the jet engine and is removed from the chamber must be replaced on a real-time basis to prevent the barometric pressure inside the chamber from becoming too low (structural integrity of the building itself must be considered). The air which is introduced to the chamber to compensate for the air which has been used by the jet engine must also be conditioned to the proper temperature. The system which accomplishes this feat is known as an Air Makeup System. At the McKinley Climatic Laboratory, the Air Makeup capacity is 1,000 lbm/sec at -65 degrees Fahrenheit for up to a 40-minute run time. If the jet engine is operated at a lower throttle setting, or if the test is conducted at chamber temperatures warmer than -65°F, less makeup air is required and the run times can be extended to several hours.

The icing condition applicable to this discussion is ground fog icing. This condition is generated with portable spray frames (built up to any size required by the customer) and wind machines. The spray frames use high pressure water and air to provide an atomized cloud with droplets normally in the 20-40 micron median volume diameter (MVD) range and with 0.1-0.6 g/m^3 liquid water content (LWC). The McKinley Climatic Laboratory can meet these requirements. However, up to 90 micron MVD and up to 0.8 g/m^3 LWC

have been generated for previous tests. Laboratory engineers believe that an even greater range is possible with little change to existing equipment.

The nozzles are steam jacketed to prevent freezing and subsequent disruption of the spray. The cloud is blown toward the aircraft at about 15-20 mph using large wind machines (much higher velocity winds are available). This condition directly simulates a stationary aircraft operating in ground fog icing conditions (such as waiting for takeoff at an airport). Evaluations also have revealed, empirically, that the ice accretions experienced in this static laboratory environment correlate very closely with ice accretions experienced during in-flight tanker icing conditions, despite the large velocity difference. As a result, for many years, the United States Air Force (USAF) has conducted this ground fog icing condition either prior to or in conjunction with icing tanker evaluations of new aircraft designs or upgrades to existing aircraft propulsion engines, nacelles, anti-icing/deicing systems, etc., within this facility.

There are a number of distinct advantages of utilizing environmental test chambers to conduct icing evaluations:

- **Year-Round Availability.** Environmental test chambers can create the required test conditions totally independent of the weather outdoors.
- **Repeatable Test Conditions.** In environmental test chambers, the climate created for the desired test conditions is generated by mechanical means. Once all of the variables are understood, means can be devised to control the appropriate variables. For the vast majority of icing evaluations, the climatic variables are limited. Temperature, relative humidity, water and air flow rates, and pressures are all controllable within certain ranges. At the McKinley Climatic Laboratory, the following variable ranges apply. Temperature within the facility can be controlled to within about ±1°F between -65 and +165°F. Maximum relative humidity (RH) is 98% or more at any temperature between 32°F and 125°F, decreasing to about 40% at 160°F. Minimum RH is 40% at freezing, decreasing to about 10% at 160°F. Below freezing, RH is not normally controlled. Water supplied to icing frames, rain frames, and snow machines can be regulated from 0 to 125 psi, providing up to several hundred gallons per minute (water flow rate required for each type of test varies widely). The water temperature can be controlled between about 65°F (city water main temperature) down to the chamber ambient temperature. Facility plant air is available regulated up to about 100 psi. This air is used for the icing frames at very low volume flow rates. The snow machines have their own onboard air compressors which also deliver air at about 100 psi.
- **Continuous Test Conditions.** In environmental chambers, the water supply is typically provided through city water mains and may be described as continuous.
- **Wide Range of Test Conditions.** In the case of icing tunnels and environmental chambers, there is considerable flexibility to experiment with various pumps and compressors to provide the necessary pressures and flow rates of water and air. Typical icing conditions requested at the McKinley Climatic Laboratory range from 20 to 40 micron MVD and from 0.1 to 0.6 g/m^3 LWC, although a wider range is available. (Figures are not given for other facilities, as the McKinley Climatic

Laboratory is the only facility currently conducting icing cloud tests (as opposed to freezing rain tests) with application to aircraft icing environments.)

- **Selectable Areas of Exposure to Test Conditions.** In an environmental chamber, a small icing cloud can be concentrated on a particular area of interest, or the entire aircraft can be engulfed in the cloud. Since the aircraft and cloud generating apparatus are both stationary, there is no question regarding spray time versus "test" time. The full-scale test item is always in the cloud. The ability of the ground facility to generate a very large cloud can alleviate the problem of nonuniformity of the LWC at the boundaries of the cloud.
- **Accessability for Ice Accretion Examination.** Environmental chambers have the advantage of being able to control the ambient air temperature. This allows for hands-on personal inspection, measurement, and documentation of the actual ice accretions. Photography and camera work are an option, not the primary means of documentation.
- **Significant Cost Savings Over Flight Test.** Flight testing is very expensive. Ground facilities have proven to be significantly less expensive.
- **Safety.** One of the primary advantages of conducting icing evaluations in a ground facility is safety. Although equipment tested within a ground facility may sustain damage from icing tests, neither the personnel nor the hardware are in danger of crashing.

These advantages make environmental test chambers another valuable tool in the investigation of icing phenomena of aircraft components.

CURRENT LIMITATIONS OF ICING SIMULATION IN ENVIRONMENTAL CHAMBERS

Environmental chambers have limitations with regard to conduct of icing tests, as do other methods.

The primary limitation of environmental test chambers lies in the types of icing conditions created. Nearly all of the large environmental chambers surveyed conduct freezing rain and snow evaluations. These evaluations may provide useful information for ground based operations of aircraft (e.g., evaluations of anti-icing/deicing equipment). However, the focus of this report is on creation of icing simulations that correlate to those conditions experienced by aircraft in flight. Only one environmental chamber currently generates such simulation conditions.

Another of the primary limitations appears to be chamber size. Most environmental chambers only have a volume of a few cubic feet. An extensive search found only seven or eight chambers that are large enough to accommodate a test item the size of a jet engine with nacelle, a wing section, or other relatively small items. (The results of this search are summarized in appendix D.)

Some of the larger chambers are:

- Wyle Laboratories at Huntsville, AL ($28' \times 18' \times 18'$);

- Naval Air Warfare Center at Pt Magu Naval Station, near Oxnard, CA (60′ × 60′ × 25′);
- US Army Aberdeen Test Center, MD (78′ × 40′ × 24′);
- Nevada Automotive Test Center at Carson City, NV (88′ × 22′ × 26′);
- US Army White Sands Missile Range, NM (105′ × 40′ × 50′); and
- McKinley Climatic Laboratory at Eglin Air Force Base near Ft. Walton Beach, FL (250′ × 260′ × 70′).

There are also uncertainties with regard to icing conditions created within environmental chambers. These uncertainties are the same as those which icing tankers and icing tunnels experience (i.e., they exist among all testers within the icing community), namely the effects of humidity, drop velocities, and drop temperature.

Finally, with regard to measurement systems, all environmental chambers tend to use manual measuring techniques for icing conditions (ice/snow depth, density, etc.). For typical freezing rain and snow type conditions, this is perfectly fine. However, to generate icing conditions that correlate to natural fog and clouds that aircraft operate within, real-time measurement of the MVD and LWC is crucial. These two physical characteristics of the icing cloud are the primary variables that influence ice accretion. They are typically measured using laser interferometers applying various interferometry techniques. This type of measuring system is employed by in-flight tankers, within the icing tunnels, and also within the McKinley Climatic Laboratory environmental chamber.

Across the entire community of testers using these instruments, there appears to be debate as to the validity of the readings these instruments typically produce. Either interpretation of the results is in question or instruments from different manufacturers (and there are only a few) appear not to agree as closely as the community would like. This concern needs some level of emphasis from the FAA if the icing community is to ultimately agree on a standardized instrument or a standardized method for calibrating instruments from different manufacturers.

APPENDIX A—TASK 11C IN FAA IN-FIGHT AIRCRAFT ICING PLAN

Task 11. Develop validation criteria and data for simulation methods used to determine ice shapes on aircraft, including icing tunnel, ice accretion computer codes, and icing tanker.

C. *SIMULATION IMPROVEMENT.* The Federal Aviation Administration (FAA) will support research on the development and improvement of ice simulation methods such as ice accretions codes, icing tunnels, and icing tankers. This research will be directed at understanding the physical processes underlying the ice accretion process, including phenomena associated with supercooled large droplet (SLD) ice accretion.

PLAN DETAILS, TASK 11C.

A working group will be formed to publish a research plan that addresses how the FAA can most cost effectively improve the simulation capabilities of industry and research facilities.

Responsible Parties: FAA William J. Hughes Technical Center, Aircraft Certification Service.

APPENDIX B—11C WORKING GROUP MEMBERS AND ATTENDEES

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APPENDIX C—RECOMMENDATIONS CONCERNING NEEDS AND DESIRED IMPROVEMENTS FROM INDUSTRY USERS OF ICING SIMULATION METHODS

The following tables (C-1 to C-4) present recommendations from industry users to address needs and desired improvements for simulation methods and facilities. This information was provided as part of gap analyses in the contributions of the industry users of the simulation methods. These recommendations support the goal of Task 11C, which is to provide information for use by research organizations in guiding their investments to improve icing simulation methods.

No prioritization of these recommendations was done by the 11C Working Group. However, examination of the tables reveals several major concerns. One such concern is the development of criteria and validation data, as necessary, for acceptance of simulation tools in certification. A large number of recommendations are listed for icing analysis computer codes. Increased use of these codes is attractive to industry in part because of their potential for improvements in cost/flow time in the design and certification processes. Issues of validation data and acceptance criteria are recognized as especially relevant to icing analysis computer codes.

The ice protection contribution did not include a gap analysis or recommendations. Thus, ice protection is not included in the tables.

No table is included for climatic chambers, since none of the user contributions included a gap analysis or recommendations pertaining to these facilities. This is a consequence of the somewhat limited use of climatic chambers thus far for in-flight icing simulation. (Use of these facilities for ground icing tests has been more extensive.) The climatic chambers offer some distinct benefits and special capabilities, and use of them to investigate in-flight icing issues has increased in recent years.

TABLE C-1. RECOMMENDATIONS CONCERNING NEEDS, DESIRED IMPROVEMENTS, AND GAPS: GENERAL OR "SPECIAL" ISSUES

Industry Segment	Recommendations: Needs/Desired Improvements/Gaps
General Aviation, Business Jets, and Commuters (Need for all icing simulation methods.)	• Validation satisfactory for FAA acceptance.
Transport Aircraft (Recommendations)	• Research investment should reflect need for industry to reduce the cost/flow time of certification process. • Icing simulation methods must establish that they meet the standards/criteria for the acceptability. • Acceptability criteria should include accuracy requirements for ice shapes and their pertinent features affecting the airplane's aerodynamic performance. • High Reynolds number icing wind tunnels are not available. The investment for a pressure icing facility would be enormous; hence, an analytic study of altitude and Reynolds number effects to determine the necessity for this type of facility might be a cost-effective alternative. This approach probably should also be used to understand the necessity for icing facilities with complete three-dimensional (3D) airplane configurations capability.
Helicopters (Comments are applicable to tunnels, tankers, climatic chambers, and spray rigs.)	• Improve understanding of limitations of methods of simulating ice accretions and producing artificial icing conditions and provide acceptance or validation of test methods. • Improve understanding of any limitations associated with scale models. • Validate methods within appropriate limitations (once limitations are understood).

TABLE C-2. RECOMMENDATIONS CONCERNING NEEDS, DESIRED IMPROVEMENTS, AND GAPS: ICING ANALYSIS COMPUTER CODES

Industry Segment	Recommendations: Needs/Desired Improvements/Gaps
Engines	
General Aviation, Business Jets, and Commuters (Desired Improvements)	• Validation satisfactory for FAA acceptance of code results. • True 3D capability. • Two-dimensional (2D) codes should work with nonlifting, nonairfoil shaped geometry. • Large droplet capability. • System modeling to include: - Clearing of ice periodically on mechanically protected regions. - Runback, incorporating heat transfer outputs from ice protection system codes. • Accurate water catch prediction. • Accurate ice shape, size, and location prediction. • Ice shape growth with shape/flow field iteration, where the flow field is recalculated to include the presence of the accumulating ice shape. • Good rime, mixed, glaze modeling at appropriate temperatures. • Short user spoolup/simple training for code users. • Ease of use. • Robust operation.
Transport Aircraft	
Helicopters (Recommendations)	• Improve ease of use of these tools. • Expand general acceptance of these codes for design work. • Validation must be brought to a higher level, so that the confidence levels and limitations are known and substantiated. • Determine how good a code must be in order to be a useful code, that is, when is a code good enough to meet the requirements of the design team and certification team.
Engines (Recommendations)	• A common axisymmetric icing code, supported by a national research organization, would ease the burden for all engine manufacturers in keeping up with the latest icing technology developments. • A 3D ice trajectory code that can accept an aerodynamic flow field solution from any commonly used flow solver is needed. The benefit of this improvement is that it would reduce the cycle time of an icing analysis.

TABLE C-3. RECOMMENDATIONS CONCERNING NEEDS, DESIRED IMPROVEMENTS, AND GAPS: ICING TUNNELS

Industry Segment	Recommendations: Needs/Desired Improvements/Gaps
General Aviation, Business Jets, and Commuters (Desired Improvements)	• Increased Appendix C coverage. • Supercooled large droplets (SLD) capability, including freezing drizzle and freezing rain.
Transport Aircraft (Gaps)	• Standards/criteria for acceptance of icing wind tunnels for airplane certification. • Accuracy requirements for ice shape and features for airplane certification for flight in icing conditions for Appendix C. • Additional icing environment simulation capability beyond Appendix C as needed. • Understanding droplet scaling effects. • Understanding Reynolds number effects on ice accretion. • Understanding low Reynolds number aerodynamic testing for ice effects on performance and handling characteristics. • 3D ice accretion testing method.
Helicopters (Need)	• Any limitations associated with scale models must be better understood.
Engines (Needs)	• Develop ability to simulate the discontinuity between icing particle temperature and the local air temperature at the component location. • Develop test rig for conducting component validation testing during the development phase of an engine program.

TABLE C-4. RECOMMENDATIONS CONCERNING NEEDS, DESIRED IMPROVEMENTS, AND GAPS: ICING TANKERS

Industry Segment	Recommendations: Needs/Desired Improvements/Gaps
General Aviation, Business Jets, and Commuters (Desired Improvements)	• Availability. • Greater spray coverage when needed. • Greater repeatability—Finding the same environmental conditions is difficult on different flights. Pilot technique dictates how a test airplane sets within the spray plume and the relative positions of tanker and test aircraft determine specific icing conditions established. Because of the cold and clear conditions sought for tanker testing, the plume will dissipate very quickly in the high, dry, nonhumid conditions. Icing conditions defined by liquid water content (LWC) and droplet size will vary rapidly with distance from the tanker aircraft. For this reason it is absolutely necessary to instrument the test aircraft with appropriate icing probes. Variable nozzles used on the Air Force Tankers provide considerable flexibility, but for tankers with fixed nozzles, the lesser flexibility can be overcome with diligent efforts. • Reasonable cost.
Transport Aircraft	
Helicopters	
Engines (Recommendations)	• Since icing on the spinner and the fan hub are often the root causes of icing problems in an engine, accurate simulation of LWC at these locations is necessary for a meaningful icing test. • Improvements to the uniformity of simulated icing clouds generated by flying tankers can significantly increase the value of this tool to engine manufacturers.

APPENDIX D—SURVEY OF ENVIRONMENTAL CHAMBERS

FAA Icing Plan – Task 11C Working Group Report
Environmental Chambers
Icing Capabilities & Limitations

01-Oct-00

	Contact		Type of Icing Condition Created					
Source / Location	**Name**	**Phone #**	**Icing Cloud**	**Frzing Rain**	**Snow**	**Capabilities**	**Limitations**	**Desire FAA Funding for...**
McKinley Climatic Laboratory (MCL), Eglin AFB, FL	Dwayne Bell	(850) 882-4610	**Yes**	**Yes**	**Yes**	250′ x 260′ x 70′ Chamber. 130′ x 29′ x 25′ Chamber. R22 Refrigerant. -65° to 165°F. Icing Cloud, Freezing Rain, Snow. Testing of full scale aircraft. Air Make-Up capability of 1000 lbm/sec in Main Chamber, 500 lbm/sec in Equipment Test Chamber (allows operation of jet engines in the environment). Measurement of Icing Cloud MVD and LWC determined with Laser Interferometer (same as Icing Tunnels). All other measurements for freezing rain and snow taken manually.	Icing Cloud testing only done at relatively low speeds (usually 15-20 mph). Winds up to 50 mph are currently available.	1. Study to compare laser interferometer accuracy between MCL and Icing Tunnel instruments. 2. Study to compare results between MCL and In-Flight Tankers.
Nevada Automotive Test Center, Carson City, NV	Henry Hodges Jr	(775) 629-2000	**Yes**	**Yes**	**Yes**	88′ x 22′ x 26′ Chamber. -70° to 170°F. Snow machines, water spray nozzles. Tank for deionized water, prechilled. Measure moisture content of snow (rent equipment), opacity monitor for suspended ice crystals in fog, crack flow detectors for freezing rain. All other measurements manual. Wind 50 mph over 8′ diameter.	Icing Cloud refers to generation of fog created for visibility testing only (suspended ice crystals). No Air Makeup.	Larger chamber to test full sized aircraft.
Wyle Laboratories Huntsville, AL	Bob Porter	(205) 837-4411	No	**Yes**	**Yes**	28′ x 18′ x 18′ Chamber. Water spray nozzles for freezing rain. Air nozzles used for snow. Tank to prechill water 35°-38°F. Depth measured manually.	Evaporators tend to accumulate ice. Chamber temperature drift during defrost cycle. Snow is wet / high density. No icing cloud. No Air Makeup.	
Naval Air Warfare Center, Weapons Division, Pt Magu Naval Station, Oxnard, CA	Greg Babcock	(805) 989-0732	No	**Yes**	**Yes**	60′ x 60′ x 25′ Chamber. R404 Refrigerant. Water spray frames in ceiling for freezing rain. Water / Compressed Air nozzles for snow. Do not prechill water. Ice and snow depth measured manually.	No icing cloud or snow simulations. No wind capability. No Air Makeup.	Wind Capability.

FAA Icing Plan – Task 11C Working Group Report
Environmental Chambers
Icing Capabilities & Limitations

01-Oct-00

Source / Location	Contact: Name	Contact: Phone #	Type of Icing Condition Created: Icing Cloud	Type of Icing Condition Created: Frzing Rain	Type of Icing Condition Created: Snow	Capabilities	Limitations	Desire FAA Funding for...
White Sands Missile Range, NM	Rick Reynaud	DSN 258-6414	No	**Yes**	**Yes**	105′ x 40′ x 50′ Chamber. -65° to 200°F. Snow machines. Hand wand for freezing rain. Tank for prechilled water. All measurements for depth and density done manually. Up to 1000 cfm conditioned air for Air Makeup (diesels, small motors). Wind machines to 50 mph with 8′ diameter.	Chamber 40′ wide but door only 32′ wide. No icing cloud capability. Only 1000 cfm Air Makeup.	
US Army Cold Regions Test Center, Ft Greely Alaska	Art Trantham	(907) 873-4597	No	**Yes**	**Yes**	12′ x 16′ x 8′ Chamber. -60°F. Low Temp testing only. All other testing done outdoors. Freezing Rain done by hand wand. All measurements manual.	Most testing done outdoors - not controlled conditions. No Icing cloud capability. Very small chamber size - no full sized vehicles. No Air Make-Up.	
US Army Aberdeen Test Center, STEAC-AC-I, Aberdeen Proving Grounds, MD	Steve King	(410) 278-7745	No	**Yes**	No	78′ x 40′ x 24′ Chamber. R22 Refrigeration (-60° to 160°F). Portable water spray rig, hand wands. Only prechill water for small items. Depth measured manually. Wind machines.	No icing cloud or snow simulations. No Air Makeup.	Icing Cloud Capability
Air Force Packaging Evaluation Activity	Carolyn Buckey	DSN 787-8434	No	No	No	10′ x 16′ x 9′ Chamber. -65°F. Low Temp testing only.	No Icing Capability at all. Temp only. No Air Make-Up.	
Yuma Proving Grounds	Mr. Pandya	(520) 328-7081	No	No	No	8′ x 8′ x 8′ Chamber. -60°F. Low Temp testing only.	No Icing Capability at all. Temp only. No Air Make-Up.	
Northrop / Grumman Chicago, Illinois	Mike Flannery	(847) 259-9600 ext 5350						
Garwood Laboratories, Pico Rivera, CA	Tim Sturkey	(562) 692-9107						